No d'ordre :.................
Année 2014

UNIVERSITE D'ABOMEY-CALAVI

ECOLE DOCTORALE DES SCIENCES AGRONOMIQUES

THESE

Présentée

POUR L'OBTENTION DU DIPLÔME DE
DOCTORAT UNIQUE EN SCIENCES AGRONOMIQUES

Majeure : Sciences Biologiques **Mineure : Sciences Agronomiques**

OPTION : Ressources Phytogénétiques et Protection des Cultures

PAR
Touré Amadou

Thème

Gestion agronomique et dynamique des mauvaises herbes dans les systèmes de riz de bas fond en Afrique de l'Ouest

Soutenue le 15 mars 2014, devant le jury d'examen :

Pr. AHANCHEDE Adam, Université d'Abomey-Calavi	Président
Pr. KOSSOU Dansou, Université d'Abomey-Calavi	Directeur de Thèse
Pr. IPOU IPOU Joseph, Université Félix Houphouet-Boigny	Rapporteur
Dr. AZONTONDE Anastase, INRAB	Rapporteur
Pr. SAIDOU Aliou, Université d'Abomey-Calavi	Rapporteur
Pr. FIOGBE Emile, Université d'Abomey-Calavi	Examinateur

No. :..................
Year 2014

UNIVERSITY OF ABOMEY-CALAVI

GRADUATE SCHOOL OF FACULTY OF AGRONOMIC SCIENCES

THESIS

Presented

FOR FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF
UNIQUE DOCTORATE IN AGRONOMIC SCIENCES

Major: Biological Sciences **Minor: Agronomic Sciences**

OPTION: Phytogenetic Resources and Crop Protection (RPPC)

BY
Touré Amadou

Theme

Agronomic management and weed population dynamics in the inland valley rice-based cropping systems in West Africa

Defended on 15 March 2014, before the jury:

Pr. AHANCHEDE Adam, University of Abomey-Calavi	President
Pr. KOSSOU Dansou, University of Abomey-Calavi	Thesis Director
Pr. IPOU IPOU Joseph, University Félix Houphouet-Boigny	Rapporteur
Dr. AZONTONDE Anastase, INRAB	Rapporteur
Pr. SAIDOU Aliou, University of Abomey-Calavi	Rapporteur
Pr. FIOGBE Emile, University of Abomey-Calavi	Examiner

Certification

I hereby declare that the studies in this thesis have been conducted under my supervision by Amadou TOURÉ, graduate student registered at the Faculty of Agronomic Sciences of the University of Abomey-Calavi, option: Phytogenetic Resources and Crop Protection (RPPC)

Thesis Director

Prof. Dr. Ir. Dansou K. Kossou

Professor of Agronomy and Post-Harvest

Dedication

To my wife Awa, and to my children Amy, Khady Fhatim, Nourah and Samirah for all their love and support

Acknowledgements

I would like to begin by offering my greatest thanks to Papa Abdoulaye Seck, former Director General of Africa rice Center (AfricaRice) for his support and his encouragement.

Sincere gratitudes go to Dr. Adama Traoré, Director General per Interim of AfricaRice for his support.

Many thanks to Pr. Dansou K. Kossou for agreeing to act as my thesis director.

I am grateful to Dr. Joel Huat for being my supervisor during the study conducted in Benin and especially for his support, patience and motivation without which I would not have been able to finish this thesis.

Sincere thanks to Pascal Marnotte for his support in drafting the research methodology for the weed survey and for discussing the research findings.

Special thanks go to Pr Ahanchédé Adam for being the president of the thesis jury.

I also truly thank Pr. Ipou Ipou Joseph for acting as rapporteur for this thesis.

I wish to thank Dr Azontonde Anastase for acting as rapporteur for this thesis.

I wish to express my gratitude for Pr Saidou Aliou for being a rapporteur for this thesis.

Many thanks to Pr. Fiogbe Emile for acting as examiner for this thesis.

I thank sincerely Dr. Jonne Rodenburg for sharing his knowledge and experience on weed science throughout the preparation of this thesis.

Special greetings go for Dr. Ibnou Dieng for helpful comments on the statistical multivariate analyses used in this thesis.

I would like to thank Pr. Mathias Becker of the University of Bonn, Germany who initiated this thesis in the late nineties in Cote d’Ivoire.

Credits go to Drs. Marco Wopereis and Koichi Futakuchi respectively, Deputy Director General and Director of Research for Development of AfricaRice and Program Leader of Sustainable Productivity Enhancement of AfricaRice for their support.

I owe a great debt to the farmers of Agbedranfo, Houinga and Vovokame in Benin and the farmers of Pounjou (Boundiali) in Cote d'Ivoire for their enthusiastic participation in the research.

I am grateful to the research team at AfricaRice and especially to Mariame Mariko for assistance with weed identification, Vodounon Mèlé Ulbricht and Adjihounme Ernest for the field assistances and data collection for the research carried out in Benin, and the late Moriba Doumbia who implemented the research carried out in Cote d'Ivoire, collected the data and confined it to field books.

I wish to express my acknowledgements to the Inland Valley Community of Practice (IVC, formerly Inland Valley Consortium) convened by the AfricaRice for grating financial support to the research conducted in Cote d'Ivoire. I am also grateful to the European Union - and IFAD-funded RAP project (Realizing the agricultural potential of inland valley lowlands in sub-Saharan Africa while maintaining their environmental services) managed by AfricaRice for the financial assistance to the study in Benin.

Table of contents

List of figures

List of tables

Abstract

While weeds are generally considered as the most important overarching production constraints in the inland valley cropping systems in West Africa, little is known about species' associations with environmental and crop management factors. Weed species' associations to seasonal and environmental factors, such as position on the catena, soils and cropping systems, were studied during two years in four seasons (dry and wet) in 45 arable fields of three inland valleys in south-western Benin. The three most dominant weed species were *Dactyloctenium aegyptium*, *Commelina benghalensis*, and *Digitaria horizontalis* on the inland-valley crests (uplands), *Ludwigia hyssopifolia*, *Corchorus aestuans* and *Ludwigia octovalvis* on the sloping hydromorphic fringes, and *Leersia hexandra*, *Ipomoea aquatica*, and *Fimbristylis ferruginea* in the valley bottoms (lowlands). *Echinochloa colona*, *Cleome viscosa* and *Talinum triangulare* were the three most dominant species in the dry-season crops (maize or vegetables), and *Leersia hexandra*, *Ipomoea aquatica* and *Sphenoclea zeylanica* in the wet-season crop (rice). *Ageratum conyzoides*, *Synedrella nodiflora* and *Digitaria horizontalis* were observed throughout the catena. Noxious weeds in inland valley agro-ecosystems are those that combine a high frequency with a high submergence tolerance and ecological plasticity, C_4 grasses, perennial C_3 species with persistent root structures, and broad-leaved species with high propagation rates.

Differences in weed control practices for crops within and across sites were noted. Across the three sites, hand weeding remained the major means to control weeds. Herbicides uses were limited because of the expense and limited cash. No significant differences were found between the different weed control practices along the heterogeneous catena positions. Within a site, the primary determinants of the weed control method used were the financial and labour resources of the farmers. The time required for hand weeding was much greater and yields lower in dry-seeded rice for poorer farmers (mainly women and part time farmers with casual employment), and herbicides could play a major role for weed control.

With regards to farmers' perceptions on weeds occurrence and management along the heterogeneous catena, farmers in the three studied areas differentiated up to 27 weed species and expressed their perceptions about their importance and mechanisms of control. Farmers listed mainly dryland weeds as important (e.g. *Imperata cylindrica*, *Commelina benghalensis*, *Euphorbia heterophylla*, *Ludwigia deccurens*, *Digitaria horizontalis*, and *Ageratum conyzoides*). Not all weeds are perceived as noxious. Some are considered as useful components in the system, even constituting vegetables during the food scarcity gap period.

A large proportion of the rice in West Africa is produced in rainfed lowland ecosystems, mainly in inland valleys. The hydrological conditions (duration and intensity of flooding) vary with the toposequence position between the valley crests and the valley bottoms. Production systems tend to evolve from the currently predominant unbunded plots without external input use, to input-intensive production in bunded plots. Agronomic management practices co-evolve and may include varietal choice, herbicide use, and mineral N fertilizer application. The response of rice and the associated weeds to such management practices is likely to vary with the prevailing hydrological regime. A two-year field experiment was conducted in northern Cote d'Ivoire to determine the impact of water regime (plot position in the valley, presence of bunds) and inputs (mineral N fertilizer and herbicide) on the productivity (yield and N use efficiency) of traditional and improved rainfed lowland rice cultivars and the biomass and composition of the associated weeds. Installing field bunds reduced seasonal variations in ponded water depth and resulted in a mean increase in rice grain yield of 30-40% (p=0.05). This increase was associated with a 25% cumulative reduction of weed biomass and a several-fold increase in the nitrogen use efficiency in the bunded compared with the unbunded plots. Under low input management, traditional rice varieties tended to out-yield improved varieties in unbunded plots. Improved crop management such as herbicide and fertilizer application, and the construction of field bunds was more effective to increase the yield and N use efficiency in the flooded valley centre than in the drought-prone valley fringes. There is a need for site-specific targeting of improved cultivars, land development and improved production practices in the inland valleys of the West African savanna zone.

Key words: Inland valley; Catena; Weed communities; Ecological profiles; Integrated weed management; Water management; Field bunds; Fertilizer application; N use efficiency; Rain-fed lowland rice; Vegetables; Benin; Cote d'Ivoire; West Africa.

Résumé

Alors que les mauvaises herbes sont généralement considérées comme les principales contraintes de production dans les systèmes de production au niveau des zones de vallées intérieures en Afrique de l'Ouest, peu de connaissance existe sur les associations des espèces de mauvaises herbes avec les facteurs environnementaux et les pratiques de gestion des cultures. Les espèces de mauvaises herbes et les facteurs climatiques et environnementaux, tels que la position sur la toposéquence, les sols et les systèmes de culture, ont été étudiées pendant deux années soient quatre saisons (deux sèches et deux humides) chez 45 paysans et dans trois vallées intérieures du Sud-Ouest Bénin. Les trois espèces de mauvaises herbes dominantes rencontrées étaient *Dactyloctenium aegyptium*, *Commelina benghalensis*, et *Digitaria horizontalis* sur les crêtes de la vallée intérieure (plateau), *Ludwigia hyssopifolia*, *Corchorus aestuans* et *Ludwigia octovalvis* sur la frange hydromorphe, et *Leersia hexandra*, *Ipomoea aquatica*, et *Fimbristylis ferruginea* dans le fond de la vallée. *Echinochloa Colona Cleome viscosa* et *Talinum triangulare* étaient les trois espèces les plus dominantes pendant la saison sèche avec les cultures maraîchères (maïs et légumes), et *Leersia hexandra*, *Ipomoea aquatica* et *Sphenoclea zeylanica* avec la culture de la saison humide (riz). *Ageratum conyzoides*, *Synedrella nodiflora* et *Digitaria horizontalis* ont été observés tout le long de la toposéquence. Les mauvaises herbes envahissantes dans les écosystèmes agricoles des vallées intérieures sont celles qui combinent une fréquence et une tolérance élevées à la submersion et qui ont une plasticité écologique (e.g. graminées C_4 et vivaces C_3 avec tubercules et stolons souterrains).

Des différences dans les pratiques de gestion des mauvaises herbes ont été notées sur les trois sites. Le désherbage manuel était la principale pratique pour contrôler les mauvaises herbes. L’utilisation des d'herbicides étaient limitée en raison du coût d’acquisition. Aucune différence significative entre les pratiques de gestion des mauvaises herbes sur les positions de la toposéquence hétérogène n’a été notée. Les principaux facteurs déterminants de la gestion des mauvaises herbes utilisées étaient la disponibilité de la main d’œuvre et les ressources financières. Le temps requis pour le désherbage était beaucoup plus important et les rendements plus faibles pour les agriculteurs pauvres disposant de ressources financières limitées (principalement les femmes et les agriculteurs occasionnels avec emploi occasionnel de main d’œuvre) et les applications des herbicides pourraient jouer un rôle majeur dans la gestion des mauvaises herbes dans cet écosystème spécifique.

Concernant les perceptions paysannes sur les mauvaises herbes, les producteurs ont différencié 27 espèces de mauvaises herbes de par leur importance et leur gestion. Pour les producteurs, toutes les mauvaises herbes ne sont pas nuisibles. Certaines sont considérées comme des auxiliaires, et consommées sous forme de légumes pendant la période de soudure.

Une grande partie de la production rizicole en Afrique de l'Ouest est faite dans les bas-fonds. Les conditions hydriques (durée et intensité des inondations) varient avec la position de la toposéquence entre les crêtes et centres de ces vallées. Les techniques de production ont tendance à évoluer des parcelles non endiguées sans usage d’intrants, aux parcelles endiguées à forte utilisation d’intrants. Des pratiques de gestion agronomique en vue de la productivité des cultures peuvent inclure les choix variétaux, l'utilisation d'herbicides et d'engrais azotées. La réponse du riz et des mauvaises herbes associées à ce type d'intervention est susceptible de varier avec le régime hydrologique qui prévaut. Des essais agronomiques ayant duré deux ans ont été menés au Nord de la Côte d’Ivoire afin de déterminer l'impact du régime hydrique (position des parcelles dans la vallée et la présence de diguettes) et l’usage des intrants (engrais azoté et herbicide) sur la productivité (rendement et efficacité d'utilisation de N) des variétés de riz de bas fond (traditionnelles et améliorées) et la composition des mauvaises herbes associées. L’installation de diguettes a réduit les variations saisonnières de la profondeur de la lame d'eau accumulée et a entraîné une augmentation moyenne de rendement de grain de riz de 30 à 40 % (p= 0,05). Cette augmentation a été associée à une biomasse cumulative des mauvaises herbes inférieure de 25 % et une augmentation dans l'efficacité d’utilisation de l’azote appliquée dans les parcelles endiguées. En condition de faibles niveaux d’utilisation des intrants, les variétés traditionnelles avaient tendance à donner des rendements plus élevés comparativement aux variétés améliorées au niveau des parcelles non endiguées. Les pratiques de gestion améliorée des cultures telle que l'application d'engrais et l’utilisation d'herbicides et la construction de diguettes était plus efficace en ce qui concerne l’augmentation du niveau de rendement du riz, l'efficacité d’utilisation de l’azote appliquée au centre de la vallée inondée comparativement aux crêtes de la vallée sujettes à la sécheresse. Ces résultats suggèrent un besoin urgent pour le ciblage de site-spécifique pour les variétés améliorées, un aménagement des bas-fonds et des pratiques améliorées de production dans les bas-fonds en zone de savane en Afrique de l’Ouest.

Mots-clés : Bas-fond; Toposéquence; Mauvaises herbes; Profiles écologiques; Gestion intégrée des mauvaises herbes; Gestion de l’eau ; Diguettes; Fertilisation minérale ; Efficacité d’utilisation agronomique de l’azote ; Riz de bas-fond; Cultures maraîchères; Bénin; Côte d’Ivoire; Afrique de l’Ouest.

Abbreviations

AHC	Agglomerative Hierarchical Clustering
CCA	Canonical Correspondence Analysis
CFA	African Financial Community
CIRAD	Centre de Coopération Internationale en Recherche Agronomique pour le Développement
DCA	Detrented Correspondence Analysis
FAO	Food and Agriculture Organization
GPS	Global Positioning System
IVC	Inland Valley Consortium
MCA	Multiple Correspondence Analysis
MSP	Multi Stake holder Platform
ONG	Non-Governmental Organization
PCA	Principal Component Analysis
PVC	Polyvinil chloride
RAP	Realizing the Agricultural Potential of inland valley lowlands in Sub-Saharan Africa while maintaining their environmental services
SSA	Sub-Saharan Africa (n)

Chapter 1

General introduction

1.1. Introduction

Inland valleys also known as ‘bas-fonds’ in francophone West Africa are largely unexploited land resources with an estimated total surface area of 85 million ha in West Africa (Windmeijer and Andriesse, 1993). These agro-ecosystems are characterized by more fertile, heavy textured soil and a generally favorable hydrological regime (Andriesse et al., 1994; van der Heyden and New, 2003). Inland valleys are therefore areas with a high potential for the development of rice-based production systems (Rodenburg et al., 2013).

Most inland valleys have an undulating topography and high spatial variability in soil and hydrology (Windmeijer et al., 2002). They are composed of adjacent land units comprising upland crests, hydromorphic valley fringes and seasonally flooded valley bottoms, and constitute the center of subsistence agriculture (Figure 1).

Intensification and diversification practices are frequently observed in the inland valleys in West Africa in order to increase food production (Erenstein et al., 2006a). Rice (*Oryza sativa* L.), vegetables and sometimes off-season maize are the most important food crops produced in these ecosystems. These crops are either grown in rotations or as sole crop, with rice during the wet season (in West Africa: May to November), and vegetables and maize growing on residual soil moisture in the dry season (West Africa: December to April). Particularly rice cultivation has expanded in the last decade, and now occupies 31% of the 3 million hectares of arable lands in the inland valleys of West Africa (Seck et al., 2012). Recently, with the high demographic growth encountered in many parts of Africa, domestic rice consumption in West Africa has increased of 8% per annum largely exceeding domestic rice production growth rate of 6% per annum, due mainly to incomes

Figure 1. Typical West African rice based cropping systems inland valley.

increases in urban areas, resulting in a shift of consumers preferences in favour of rice (Balasubramanian et al., 2007).

Most inland valley rice based systems in West Africa are characterized by slash-and-burn systems. With increasing land shortages, the length of fallow between periods of cultivation has declined from 12 years in the 1980s to less than three years at present, with permanent cultivation emerging in some high population areas (Giertz et al., 2012). Land use intensification in these low-input systems results in declining yield levels, which are associated with more weed pressure, a reduced soil N supplying capacity and widespread P deficiency on the predominant acid soils (Becker and Johnson, 2001).

1.2. Problems statement

Biological and physical factors, such as weed infestation, low soil fertility, poor water management are limiting inland valley rice based crops yields of West Africa (Seck et al., 2012). The demographic pressure and emerging land shortages largely prevent the opportunity to increase yields through area expansion, leading instead to the need for increasing the cropping intensity and the yield per unit land area along the inland valley slopes. The extent of slopes uses is likely to intensify weed growth dynamics, water and nutrients fluxes and thus to differentially impact fertility and crop productivity (Bognonkpe, 2004). Several weed problems have been reported in West African inland valleys along the catena. The hydrological gradient (largely influenced by the rainfall pattern and the hypothetical climate change) that occurs in the catena from the free-draining valley crest, through hydromorphic areas, to the seasonally flooded valley bottom also has a distinct influence on the composition of weed flora (Figure 2). Certain weeds which, for instance, dominate in the valley crests areas and may not be present in valley bottom areas and vice-versa. Hydromorphic areas will often contain weeds which are found on either crests or valley bottom areas (Johnson and Kent, 2002). Since the valley bottoms dry out during the dry season, dryland crests weeds that are able to complete their life cycle on residual moisture thrive well in this ecology during the dry season (Akobundu, 1987).

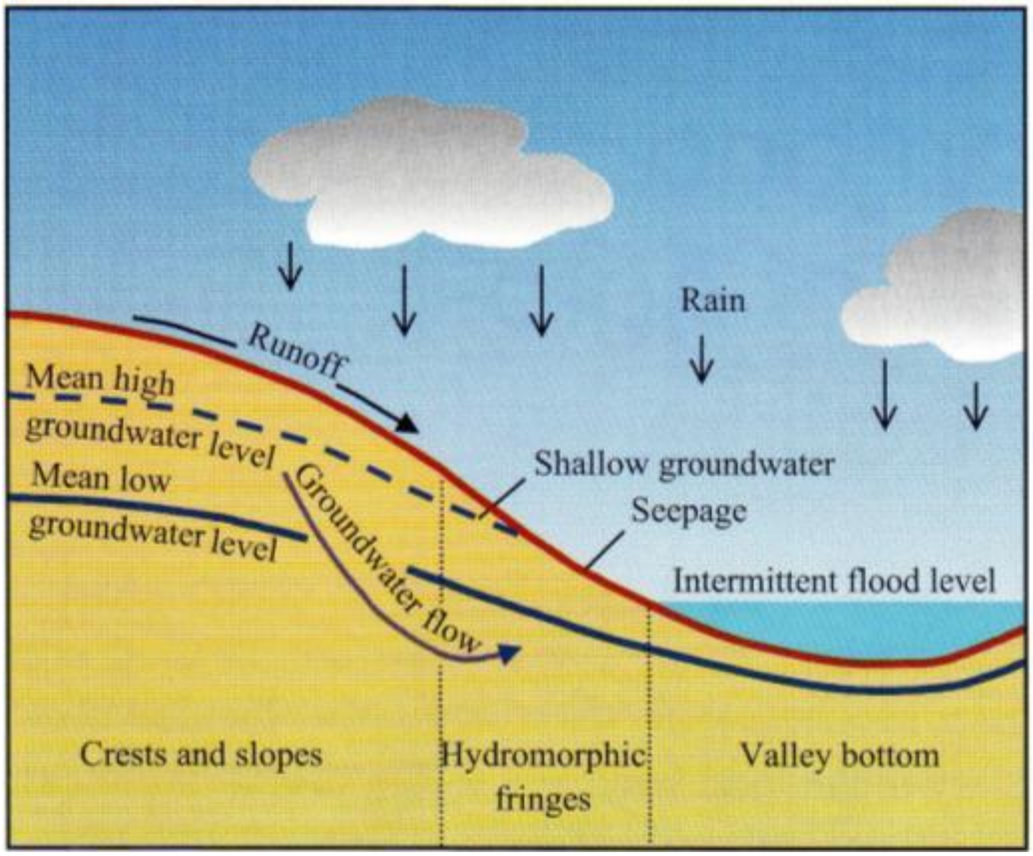


Figure 2. Landscape elements and hydrological gradients along an inland valley catena (Windmeijer and Andriesse, 1993).

Apart from the position on inland valley catena, weed growth dynamics are likely to vary with the cultivation practices. Farm work mainly uses the family's labour, and the technical operations are mostly manual. Hence land preparation is mostly done by hand and fields are often inadequately bunded and levelled resulting in uneven flooding and patchy conditions favouring weed growth (Rodenburg and Johnson, 2009). Given the time required for preparing the land, sowing, and weeding during the growing season, farmers are under the main constraint of fast weed growth. The scarce factor in this region's agricultural system is therefore time, as it is in most of Africa's savanna zones (Milleville and Serpantié, 1991). Given this time limitation, work organization or labour issue on the diverse farms or production units must be taken into account in cultivation practices for lowland rice based crops. Lowland rice and vegetable crops are sensitive to competition from weeds at the start of their growth cycles: weeds cut yields severely, especially if they are present during the first 40 days after sowing (Akobundu, 1987). Uncontrolled flooding also renders the use of herbicides less effective (Akobundu, 1987). The lack of a permanent and adjustable water layer favors weed infestations and leads to severe crop–weed competition and few suitable weed control technologies are yet available for farmers in these rice production ecosystems (Rodenburg and Johnson, 2009).

Due to sediment deposition in the valley bottom, inland valleys are often characterized by a gradient of soil texture, and related physical and chemical properties, with coarser soil texture on the valley crests or crest and increasing finer textures going downslope. Seasonal flooding is most likely to occur in the valley bottom while drought is common on the fringe (Ogban and Babalola, 2009). Hence, apart from a soil fertility and texture gradient there is a hydrological gradient along the catena (Carsky and Masajo, 1992).

Gradients along inland valley catena have been used to study response of crops to stresses. Bognonkpe and Becker (2000) used the catena in derived savanna zone of Cote d’Ivoire to quantify rice grain yields with soil moisture levels. Thus, the catena of West African inland valleys presents a heterogeneous continuum of biotic (weeds) and abiotic hydrologic and edaphic (soils) conditions resulting in variable crop growth. The introduction of improved varieties with high yield potential is a promising option, though most experts concur that complementary weed management and soil fertility management practices and land development are needed. A quantitative understanding of the weeds, water and nutrients dynamics along the heterogeneous catena and the crops management practices affordable by smallholder farmers in the low-input systems of the inland valleys is needed in order to improve the spatial targeting of technical options aiming at better managing weeds and maximizing water/nutrients use efficiency.

1.3. Objectives, research question and hypotheses

The main objective of this study was to analyze and to have a better understanding of the system dynamics and the sustainability of rice-based systems along the heterogeneous inland valley catena of Benin and Cote d'Ivoire in West Africa.

The specific objectives were:

- To have a better understanding and quantify the factors which influence weed communities of rice-based systems along the inland valley catena
- To define factors and determinants which influence farmers' practices and perceptions in weed management along the inland valley catena
- To comparatively evaluate at various landscape positions within an inland valley a number of technologies commonly applied along the inland valley catena and influencing rice grain yield.

These observations on the tremendous variability of conditions along the inland valleys catena raised the following research question: how do the diverse West African lowland rice farmers integrate the heterogeneity of conditions found along the catena of the inland valleys in their crops management? As an answer to this research question, the following hypotheses were formulated:

- Hydric regime and/or cropping systems based on crop rotations may influence weeds communities and weed covers of a given landscape position along the heterogeneous inland valley catena

- Diverse production units mainly determined by labour force and household incomes may influence cropping practices along the heterogeneous inland valley catena and consequently weed species occurrence and abundance, and crops yields, and farmers' perception of weeds and vice versa
- Crops yield responses to improved weed control, better water control and application of mineral fertilizer, will depend on interactions of environmental factors and other management practices, and are likely to vary with the hydric regime of a given landscape position on the heterogeneous inland valley catena

Chapter 2

Literature review

2.1. The inland valleys

Inland valleys representing the centers of subsistence agriculture constitute the major rice growing environment in West Africa and vary from upland in the highest parts through hydromorphic conditions lower down the slopes, to swampy in the valleys bottoms; and present different forms of water regimes according to the agro ecological conditions (Figure 3). In savannah zones with less rainfall and rectilinear topography, inland valleys tend to be wider while those in forest areas with high rainfall and convex topography tend to be relatively narrow with frequent water logging without a distinctive stream net (Windmeijer and Andriesse, 1993). Whereas, Raunet (1985) defines ‘bas-fonds’ as flat to concave valley sections and small valleys, as well as lowered drain channels, which have no distinctive stream net. Thus the term ‘bas fonds’ is widely used in francophone West Africa.

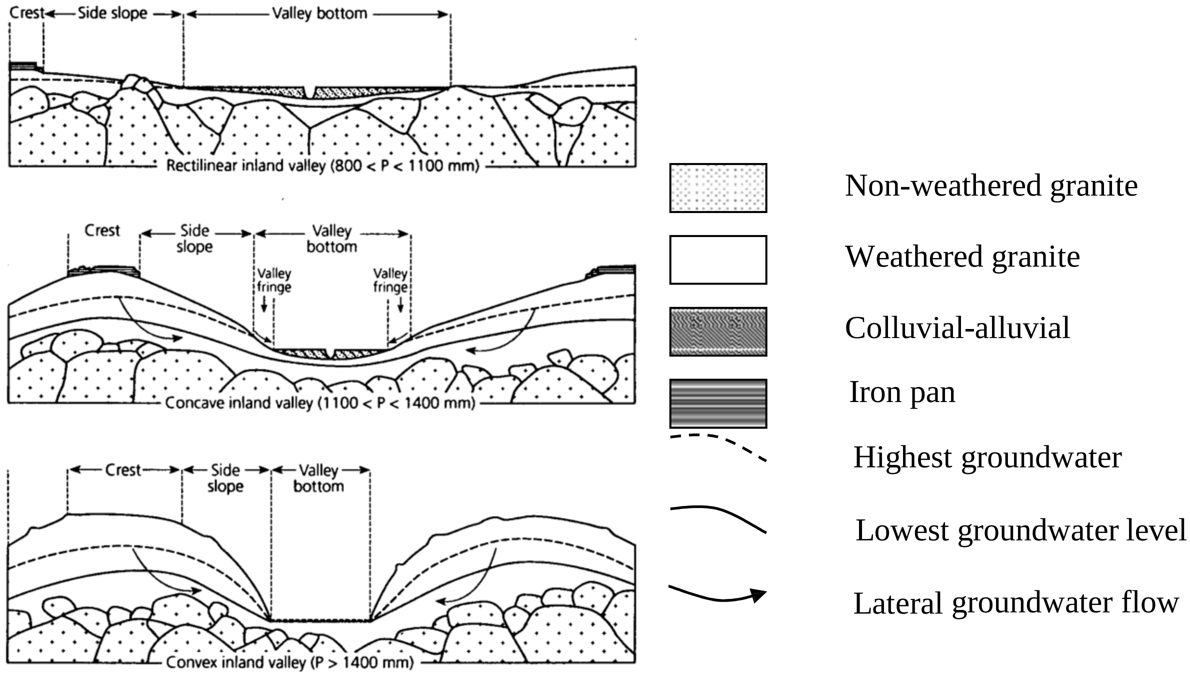


Figure 3. Cross-sections of inland valleys of West Africa; adapted from Raunet (1985).

Both terms (‘inland valley’ and ‘bas fonds’) are often used synonymously. Other regional names for ‘bas-fonds’ are ‘fadamas’ in Nigeria, ‘bolis’ in Sierra Leone or ‘mare’ in Senegal. In other parts of Africa ‘bas-fonds’ are also known as ‘dambo’, ‘mbuga’ or ‘vlei’ (Giertz et al., 2012).

In Inland valleys, river alluvial sedimentation processes are absent or slightly important (Windmeijer and Andriesse, 1993). In the uplands (crests and slopes) the only source of water is precipitation. This area is well drained, because excess rainwater is not stored in the soil and is discharged superficially by runoff, or by deep percolation to the groundwater. The hydromorphic fringes or the phreatic zone, groundwater together with rainfall is the major source of water for plants, at least during the rainy season but also in the beginning of the dry season. The valleys bottom or the fluxial zone is saturated and inundated in the rainy season and, depending on the climate and the morphology of the valley, during a certain period after the rains have stopped. The main sources of water are surface flow (runoff from the uplands and flooding by the stream if present), groundwater inflow from the uplands, and precipitation. According to Windmeijer and Andriesse (1993), longitudinally an inland valley can be divided into three parts, the valley head, the midstream and the downstream part, each with its own morphological characteristics (Figure 4).

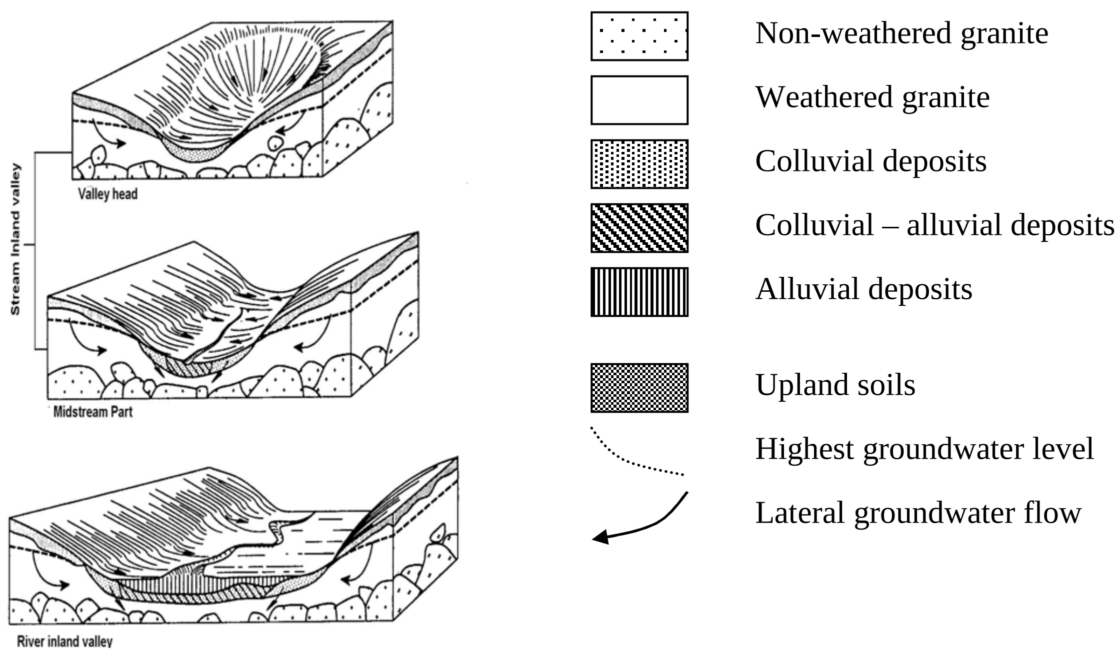


Figure 4. Valley head, midstream part, and downstream part of an inland valley; after Raunet (1985) cited by Windmeijer and Andriesse (1993).

The valley head constitutes the most upstream part of the valley. It has a concave cross-sectional profile with no stream channel and the morphology and the soils are dominated by colluvial processes. The midstream part is wider, the central part of the concave valley bottom is almost flat and a shallow, centrally-located stream channel is present. Although some river flooding and associated sedimentation may occur, colluvial processes dominate the morphology and the soils. The downstream part of the valley shows limited development of levee systems and alluvial soils occur (minor floodplains). River flooding and subsequent sedimentation is more important than in the upstream part but colluviation remains important at the fringes of the valley bottom. The uppermost part of the inland valleys is defined as the stream inland valley comprising the valley heads and the midstream parts. Stream inland valleys have an imminent, centrally-located stream channel, which is shallow and few meters wide, depending on its presence. The morphological processes in stream inland valleys are dominated by colluviation. They extend over distances of up to 25 kilometers and more. River inland valleys occur downstream of the stream inland valleys. They are wider and have a larger, and more distinct, water course. As alluvial processes are more important than in the stream inland valleys, there is some floodplain development and the stream channel is not centrally located.

Overall, inland valleys and particularly the lowland ecosystems offer good potential for rice systems intensification, because water is available, soil natural fertility is relatively high, and there is an opportunity to grow more than one crop per year. Other minor uses of inland valley are fish production, animal husbandry, collection of firewood and medicinal plants, and clayey brick fabrication, etc. Inland valleys area coverage in West Africa is estimated at around 85 million hectares (Windmeijer and Andriesse, 1993).

In the study areas of Benin and Cote d'Ivoire, inland valleys are the dominant physiographic units. Valleys are formed in one major agroecological zone (AEZ) of the countries, namely the Guinea savanna zone. In the northern part of this zone concerning the site in Cote d'Ivoire, the precipitation regime is monomodal. The mean annual rainfall varies between 1100 and 2500 mm in the west and from 900 mm to 1500 mm in the east. The radiation characteristics are favourable for plant growth. In the southern part of this AEZ covering the site in Benin, the precipitation has a bimodal pattern. The two rainy seasons are of unequal duration and rainfall is irregular. Drought hazards occur here and the radiation is sub-optimal (Windmeijer and Andriesse, 1993).

The value of mean annual rainfall lies between 1000 and 1500 mm. Hence, the agro-ecological conditions are less favourable than in the north. The main constraint to crop production in the zone with the bimodal regimes is the irregularity in precipitation, especially within the cropping seasons. The Guinea savanna zone covers 1.35 million km^2 or 42.9% of the inland valleys of West Africa (Windmeijer and Andriesse, 1993). Cotton and oil palm are the main cash crops, while maize, rice, cassava, various kings of vegetables, sugar cane and spices plants are the main food crops. Livestock concerns few domestic animals such as goats, sheep, chickens or pigs. In few cases, fishes also are raised in fish ponds. Subsistence-oriented farming systems with smallholder farmers are located in inland valleys. This farming system is based on the natural soil fertility and the use of manual labour mainly. There is few to no external input of capital, technology, manure, or fertilizers (Windmeijer and Andriesse, 1993). Despite the higher natural fertility of valley bottoms, some farmers are reluctant to cultivate in this ecology. This is because of the difficulties in the initial clearance of the wetland vegetation, the possibility of mixed cropping on the uplands, and the unhealthy working conditions with water-borne diseases such as schistosomiasis (bilharzia), trypanosomiasis (sleeping sickness), onchocerciasis (river blindness) and dracontiasis (Guinea worm) (Windmeijer and Andriesse, 1993).

2.2. The importance of rice

In 2012, Sub-Saharan Africa (SSA) imported more than 10 million tons of milled rice (*Oryza sativa* L.) worth estimated US $ 5 billion, which represents a serious drain on foreign currency reserves, aggravating the poverty and food security situations (Figure 5) (Seck et al., 2012).

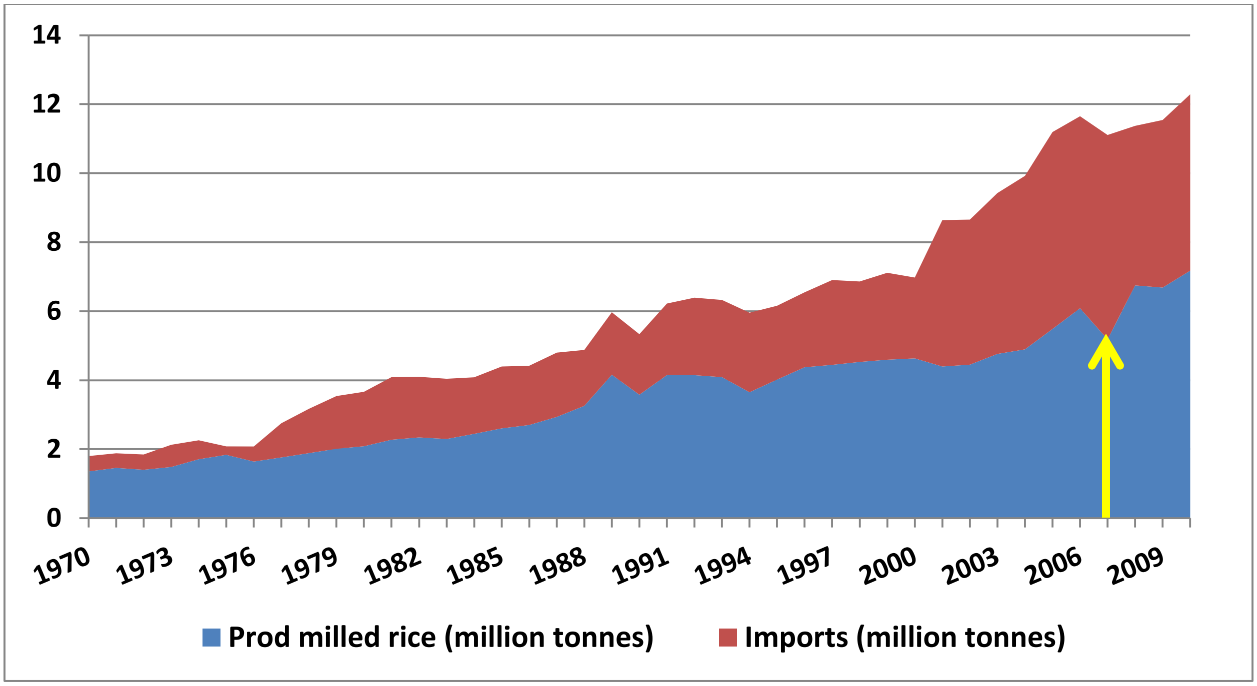


Figure 5. Evolution of milled rice production (prod milled rice), demand (imports) and 2008 rice crisis (yellow arrow) in Sub-Saharan Africa (1970-2010) (AfricaRice, 2011).

Recently African countries have been ranked among the highest in rice consumption due to a high rate of population increase of 4% per year, and due to incomes increases in urban areas, resulting in a shift of consumers' preferences in favour of rice (Balasubramanian et al., 2007). From 2001 to 2009, domestic rice consumption in West Africa increased at 8% per annum, thus largely exceeding domestic rice production growth rate of 6% per annum. Only 30% of the production increase was through productivity increase while 70% was attributed to land expansion (FAO, 2010). The main consequences of this discrepancy in rice demand and production was the rice crisis in 2008, triggering violent riots in many African cities (Figure 5). At global scale, the main reasons for the rice crisis comprised soaring prices of fuel and derivative products such as fertilizers and pesticides, market speculation, export bans and decline in water availability resulting from climate change and the recent reliance of some industrialized countries on biofuels, partially produced in the developing African countries (AfricaRice, 2011). Thus, rice has become the most important food crops in terms of cultivated surface. In the inland valleys, rice has become the dominant crop.

2.3. The rice cultivation in inland valleys

Rice is grown in diverse growing environments within the inland valleys, ranging from strictly rainfed uplands to frequently waterlogged lowlands. The rice is adapted to a wide range of soil conditions, provided there is adequate water. In West African inland valleys, rice is grown on Alfisols and Inceptisols (Bognonkpe, 2004). The relative distribution of these soils types depends on agro ecological zones, surface relief and landscape position (upland crests, hydromorphic fringe, and valley bottom). Thus, Alfisols dominate on the crests positions while the valley bottoms are characterized by Inceptisols where the huge part of inland valley rice is grown as lowland rice (Bognonkpe, 2004). Lowland rice refers to rice crop at the valley bottom in periodically flooded fields. In low inputs systems, one single rice crop is either dry-seeded in traditional rainfed lowlands (unbunded plots) or transplanted in improved lowlands (bunded rainfed plots) during the wet season. A double rice crop or dry season vegetables are possible when the system is equipped with a rainfed stream derivation or artesian well which can provide water during the dry season. The rice yield ranges from 1.4 to 2 tons ha^{-1}. Sometimes, dissolved Fe ions in inflows lead to Fe toxicity in lowland rice (Sahrawat, 2010).

2.4. The vegetables cultivation in inland valleys

The major vegetables included in West African inland valleys are: (1) leafy vegetables (e.g. *Corchorus olitorius*, *Amaranthus* spp., eggplant (*Solanum* spp.), *Celosia* spp., bitter leaf (*Vernonia amygdalina*) and water leaf (*Talinum triangulare*); (2) vegetables with edible fruits (e.g. tomato, okra, pepper, eggplant (*Solanum* spp.), green beans; (3) bulbs, roots and tubers (e.g. onions, carrot, potato and sweet potato). These vegetables are often located in the hydromorphic fringes and valley bottoms where there is either residual moisture or access to irrigation facilities to support vegetable productions during the dry season. Most often, those vegetables are cultivated on small plots with few external inputs but with relatively high manual weeding frequency, and are considered for home consumption (Akobundu, 1987). Although cultivation of vegetables on medium to larger plots involves a more intensive approach, including insecticide spraying and fertilizer applications, while the presence of a nearby market becomes important.

2.5. Diversity and evolution of lowland rice-based systems

The type of agricultural technology, their adoption potential and their effect and effectiveness depend on the rice-based production systems. These have evolved over time from the domestication of rice and traditional low-input subsistence production to high-input market-oriented precision agriculture in peri-urban or otherwise infrastructurally favoured environments. The key feature driving this evolution is the availability of the production factors land, labour, capital and know-how (Figure 6).

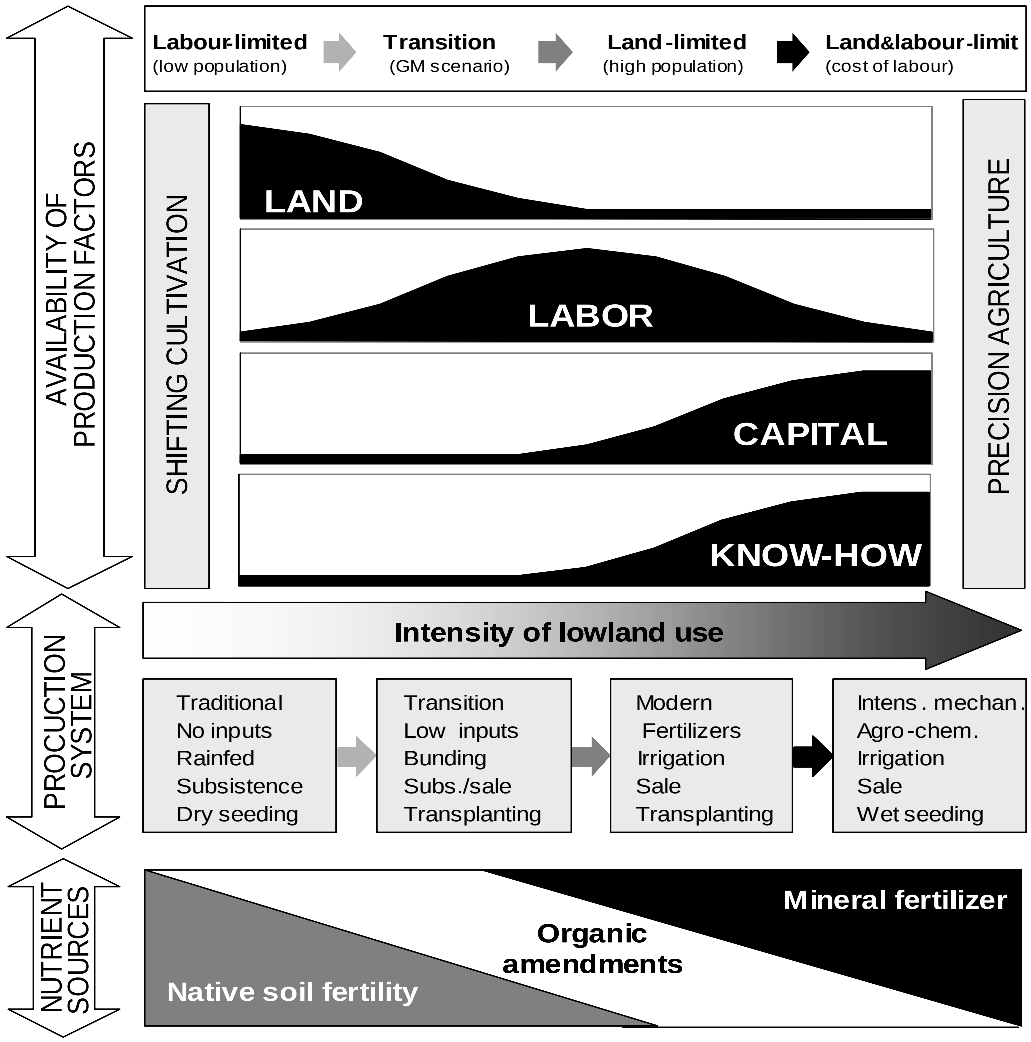


Figure 6. The conceptual evolution of lowland rice production systems (Becker et al., 2003)

In the traditional rainfed lowland systems, only a minor proportion of the available land is used (accounting for 29% to 40% of rice area in Cote d'Ivoire) (Becker and Diallo, 1992). Agricultural production is limited by the availability of labour rather than land. A low population density relative to the resource base, subsistence-oriented production objectives and a reliance on household labour characterizes these traditional extensive land use systems. Only parts of the lowlands area are used for growing a single crop of dry broadcast or dibble seeded long-duration rice cultivars, often in rotation with natural fallow. Land preparation is frequently done by slash-and-burn and only panicles are harvested. The crop has to rely on the native soil nutrient supply for its nutrition. This production environment characterizes large areas in Africa. Land availability is not limiting the production. The challenge for farmers is rather how best to allocate labour between different enterprises. A substitution of labour by capital is restricted by the unavailability of cash in the subsistence-oriented production. An investment in any type of organic amendment is not attractive, as labour is limited. Increasing the area of production can easily counteract low yields resulting from unfavourable ecological conditions or from nitrogen deficiency. The only technical option available is the use of improved seeds together with appropriate crop management techniques (mechanization).

During the subsequent transitional stage, the lowlands start to come under pressure from rising population levels. Lowland farmers introduce bunding as the first step towards improved water control and to maximise the output from the increasingly limiting resource land. The availability of labour permits the shift from dry seeding to transplanting of rice. Where they can, producers turn increasingly to the market. The availability of both land and labour combined with a still restricted access to factor markets for the purchase of mineral fertilizers are conditions favouring the use of organic amendments in this development stage. Other options relate to improved planting technologies, low-input options such as seed priming and/or the use of cultivars adapted to erratic hydrology (alternating drying and wetting of soils), weed suppression and adaptation mechanisms to prevailing nutritional stresses (iron toxicity, low phosphorus availability). Today, environments with a single crop of transplanted rainfed lowland rice are restricted to remote and infrastructurally unfavoured regions.

Beyond this stage, pressure on land for agricultural goods, but also for settlement and other non-agricultural activities continues to rise as can be observed throughout much of South and

Southeast Asia. Production is once again limited by labour as emerging markets in the growing urban centers increase the cost of agricultural labour. Land and labour are increasingly substituted for by capital such as external inputs (fertilizers, pesticides) and mechanization. Direct wet seeding combined with an intensified use of herbicides replaces the transplanting of lowland rice as it is currently happening in some of the intensively used and largely market-oriented rice-growing areas of the region (Malaysia, Thailand, the Philippines, Vietnam, Indonesia, and India). At the same time, the developing infrastructure improves access to agricultural extension and other means for the acquisition of know-how. Rice double-and triple-rice-vegetables cropping systems dominate the humid tropical zone of Asia as well as the fully irrigated areas while rice-wheat and rice-vegetable rotations emerge in the partially irrigated environments (Northern Nigeria, peri-urban fringes). Neither the land required for the production nor the labour required for the application of organic amendments is available. Mineral fertilizers replace organic amendments to meet the crops' nutritional requirements, pesticides substitutes for possible sanitation effects (e.g. nematode control or weed suppression) by organic substrates, and soil physical improvements may be addressed by secondary raw materials from the urban centre or by animal manures from intensified peri-urban rearing systems. The only exceptions are systems producing for the emerging markets for organically produced food. Hence, the changing availability of production factors drives not only the evolution of the lowland rice-based production systems, but it also determines the suitability of technical options. As systems intensify, the availability of production factors drives the evolution of the system. The trigger for a technological change is often a loss in production potential (i.e. by degradation processes). A reversal of such degradation or the loss of production potential requires a technological change (introduction of a site-and system-specifically adapted technology) leading to the different phases of the system theoretical concept.

Any natural or anthropogenic system typically moves through cycles that start with a steady state (initial stable of variable duration), a subsequent phase of destabilization and break-down, usually triggered by an external event or stress factor (chaos phase), and a reorganisation phase that eventually culminates in a new phase of stabilization (Elmquist et al., 2003; Loreau et al., 2002) (Figure 7).

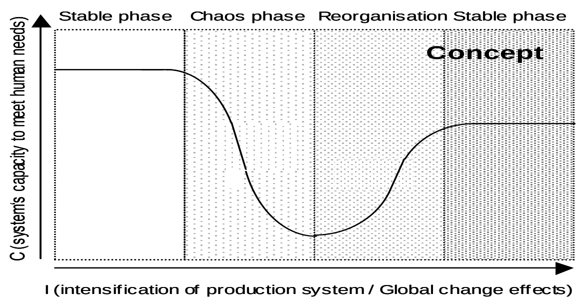


Figure 7. Phases of systems' evolution (Elmquist et al., 2003).

The extent to which a system loses its ability to provide services or meet human demands is determined by its resilience or vulnerability (Elmquist et al., 2003). The speed and extent of reorganization necessitates and is driven by the appearance or implementation of (external) modifiers.

In many traditional wetlands of West Africa, the systems are being destabilized and have in some instances reached the chaos phase, wherein the agricultural production system is unable to meet a growing human demand and a weak socio-economic and political environment prevents further destabilisation (destruction of agricultural land and forest, drought, hunger, outbreak of water-borne diseases in inland valleys, poverty, migration) or a desired reorganization (vulnerability scenario, Figure 8).

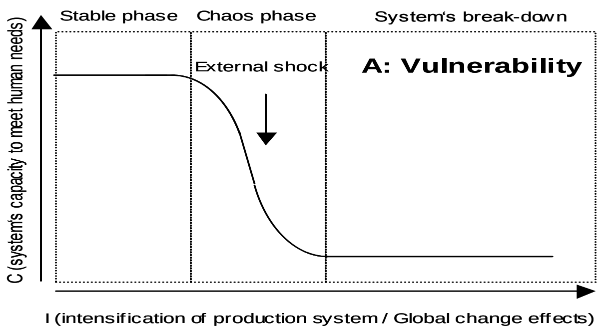


Figure 8. The vulnerability scenario (Elmquist et al., 2003).

Two strategies may be envisioned: scenario 1 aims at increasing the systems resilience under prevailing land use patterns (Giller et al., 2004). Key elements of this stabilisation include (1) an alleviation of production risk by agricultural crop diversification and enhanced soil organic matter content (i.e. crop residue management) and (2) the “cultivation” of biodiversity in view of producing forest services on farm (resilience scenario, Figure 9). Such efforts can only be sustainable if they additionally address key livelihood demands (i.e. provision of animal feed, fuel wood, etc...) (Fresco and Kroonenberg, 1992; Elmquist et al., 2003).

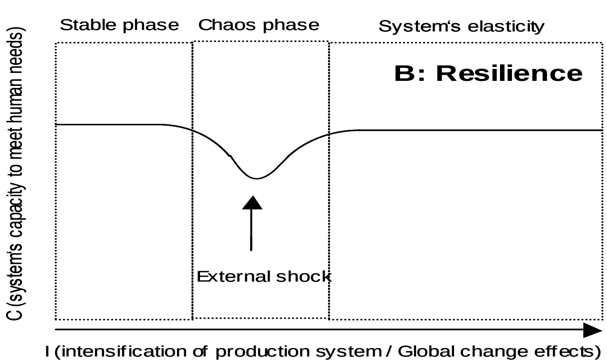


Figure 9. The resilience scenario (Elmquist et al., 2003).

Scenario 2 assumes that a reorganization or increased agricultural production potential is only possible through technical changes (Becker and Johnson, 2001; Becker et al., 2003). Provision of alternative income sources and/or the introduction and adoption of agronomic technologies that address key livelihood demands and correct key production constraints must be site-and system-specifically adapted to resource endowment of the farmer (recovery scenario) (Murdock et al., 2010) (Figure 10).

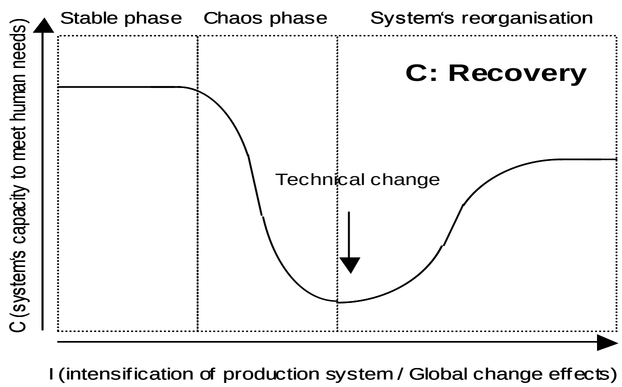


Figure 10. The recovery scenario (Murdock et al., 2010).

Implementing a combination of both scenarios is seen to reduce the anthropogenic risk factors for intensification and sustaining the livelihood of the rural population (Murdock et al., 2010).

2.6. Intensification or extensification of rice based systems

The agricultural land use in West Africa follows three trajectories. The first trajectory is extensification or expansion of cultivated land area: increasing production by expanding the area under cultivation while maintaining or reducing aggregate input levels per unit area. Most of West Africa's traditional lowland rice systems are characterized by relatively extensive agricultural systems – a reflection of the generally low population density, limited capital resource endowments, and markets access constraints.

The second trajectory is intensification: increasing production per unit area through more intensive production practices. It comprises two distinct forms: land use intensification and technological intensification. Land use intensification is defined as the number of years a plot of land is cropped in one complete crop/fallow cycle. Ruthenberg (1980) ranked cropping systems according to land use intensity as the proportion (%) of area under cultivation in relation to the total area available for farming. A cropping intensity of 33% is termed shifting cultivation. Intensity from 33% to 66% is called fallow rotations. And intensity greater than 66% is considered to be permanent cultivation. Under traditional shifting cultivation, with a Ruthenberg Index of 5% to 10%, the cropping system is in complete ecological balance with the environment. The technological intensification is defined as capital and/or labour increases of inputs use per crop per unit area. In fine, land use intensification and technological intensification are associated, and technological intensification often enables land use intensification.

The third trajectory is diversification: increasing the value of agricultural production per unit area by reducing the intensity of repetitive rice monocropping with the introduction of higher-value nonrice crops such as vegetable, grain-legumes, or higher-value root crops grown in aerated soil with irrigation during the dry season (Erenstein, 2006a). However, significant diversification of rice systems implies a significant reduction in rice area, thus putting more pressure on achieving higher rice yields from the remaining rice area, most of which is cropped in the rainy season when yield potential is lower than in the dry season. Thus, diversification may lead to deficits in rice supplies and further increase rice prices. Because rice will continue to be the most important staple food in many Western Africa countries, in both relative and absolute terms, diversification may have a negative impact on urban and landless rural poor who depend on rice as their basic food (Hossain and Fischer, 1995). Despite these problems, trends towards diversification, induced by changes in relative prices of rice versus nonrice crops, are already apparent in some intensive rice-growing areas of West Africa. The choice of the agricultural strategy (extensification, intensification and/or diversification) is probably a reflection of both bio-physical (e.g., climate and water) and socio-economic (e.g., population growth, market pull and access) factors (Erenstein, 2006a). Generally throughout West Africa, with population increase and growing market access, the intensity increases in rice growing environments is likely to be low as the duration of fallow period is insufficient to suppress weeds and maintain soil fertility (Fehlberg, 1989; Sanchez, 1976). These two constraints need to be corrected through technological change such as external input use, improved varieties and system-specifically adapted and adoptable crop management approaches. Furthermore, combining the resources use of the agronomic technologies with its dependency to market access can allow the classification of different groups of technologies in various lowland rice growing agro ecologies in West Africa (Erenstein, 2006a) (Table 1).

Table 1. Typology of technological options (Erenstein, 2006a).

Resource use of technology	Dependency of technology on market access for procurement	
	Dependent	Non-dependent
Land saving	Fertilizer, pesticide, improved seed	Bunding, transplanting, improved seed
Labour saving	Herbicide, improved seed, mechanization	Direct sowing, animal traction, improved seed
Water saving	Modern dam, reservoir	Bunding, terracing

There are technologies such as improved seed and bunding which have dual traits. Improved seed can have land and/or labour traits, because it can save land by reversing shifting cultivation to permanent cultivation in an intensive pattern with use of fertilizer. At the same time in the same intensification husbandry, it can save labour when herbicide is used. The same improved seed can also have varying dependencies on market access for the procurement, mainly for a crop such as rice where reuse of seed by farmers is common (Erenstein, 2006a). It is estimated that by 2025, the majority of West Africans will be living in countries where shifting cultivation will have completely disappeared (Murdock et al., 2010). It is where farmers have undergone the transition from shifting to fallow and permanent cultivation that there is the greatest need for technical change. The sustainability of current agricultural production by resource-poor rice farmers continues to erode as average farm size decreases, and farmers are forced onto increasingly marginal land by worsening socio-economic, political conditions and social unrests, leading to an increase in rural poverty.

2.7. Sustainability of rice based systems

A sustainable land use implies the maintenance of soil physical, chemical and biologic properties while maintaining or increasing current output without increasing dependence or external inputs (Beets, 1990). Sustainable agriculture system is intimately related to commodity and farming systems research. The objective of commodity research is the development of intensification technologies such as the better weeds management with improved varieties and efficient fertilizer use. Thus, sustainable agricultural rice systems seek to unravel the long-term implications of farming systems intensification and to introduce adapted and adoptable technologies for intensification technologies to the diverse socio-ecological niches in lowland systems of the region on the environment and on the farming systems.

As stated by Beets (1990), sustainable technologies for a particular cropping system must meet the following criteria: (1) they must enhance the efficiency of renewable resources found within the farm rather than increasing farmer dependency on external inputs (2) they must not result in soil and water degradation and depletion (3) they must be able to be adopted independently and incrementally and (4) they must preserve the farmers' management autonomy.

Although inland valleys can constitute the centers for intensification and sustainability of rice production systems, land tenure also plays an important part in the agricultural production as the social rules registering the land governs any development action to be undertaken.

2.8. Land tenure

The customary land tenure systems of the indigenous peoples are similar in many parts of Sub-Saharan Africa in that they are founded in religious belief with ancestral rights of access to land use guarded through time (Becker and Diallo, 1992). Whereas immigrant farmers are considered as people who have come to the land of indigenous peoples without displacing them. Relations between these groups have played an important role in rice agricultural development in inland valleys. It was found that immigrants are subjected to payment of rent to have access to land and have less stable access to arable land than indigenous farmers. And movement in and out of the wage labour sector by immigrant rice farmers is perhaps a more excepted part of life than of an indigenous farmer. In this situation, immigrant farmers will not invest in long-term improvements such as soil fertility improvements, soil conservation, efficient bund and irrigation canal constructions, and the planting of trees. But on the other hand, if they are long-term tenants (indigenous or immigrants for several generations), and are totally dependent on the land for their daily livelihood, they are likely to take good care of it by investing in long-term investments. Thus on ethnographic and sociological issues, inland valleys developments face major constraints coming from land tenure issues. A major deterrent to intensification of rice production is that the customary inheritance rules are thwarted against women who are the backbone (performing most of the sowing, weeding and harvesting activities) of the rice production in most inland valleys of West Africa; they are unable to inherit land. And being not land-owners, they are not involved in decision-making and adoption of technological interventions delivered by agricultural extension (mechanization, access to accredits to purchase inputs such as fertilizers, herbicides and pesticides) (Huffman, 1987). However, women farmers cultivate land they receive from the male relative of their families (Saïdou et al., 2007). But throughout West Africa, various sustainable and sound land tenures arrangements are found. Individuals can have access to land through purchase, inheritance, gifts, sharecropping or renting, and usufruct (Le Meur, 2002). Sharecropping is similar to land renting, and payment is made in kind based on fractions of the crops produced, and in Cote d'Ivoire, the system is best known as *Abusa*, where land user pays one third of the crop produced to land owner (Berry, 1993). In usufruct system, indigenous farmers obtain access to land through interfamilial inheritance and/or transfers of rights from local village leaders. Despite the different land tenure arrangements between indigenous and immigrant farmers, in recent times, increased pressure on land and new laws on land reforms have resulted in conflicting interests between indigenous landowners and immigrant farmers. Nonetheless, study of Saïdou et al. (2007) in Central Benin showed that good relationship among migrants and landowners can be established through the adoption of best soil fertility management with perennial trees planting. Indeed, secure land-ownership (title, and thus collateral) can increase rice productivity, by allowing access to credit and purchase of inputs such as fertilizers and improved seeds (Feder and Noronha, 1987). And in fine, secure ownership lead farmers to intensify rice cultivation by investing more in inland valleys developments land technologies such as water management (water supply canals) and efficient weeds control methods (Sakurai, 2006).

2.9. Water management

The duration and the depth of flooding and fluctuating of water level determine the potential of inland valleys for wetland rice production. Without water management, the periods and depths of flooding vary strongly with the climatic conditions in a certain period, but also with the topography. In wet years, the flooding can suffocate the rice plants and be too long for the rice crop to mature; in dry years, the rice crop water requirements will not be met (Windmeijer and Andriesse, 1993). Potential cropping sequences are factor of rainfall and soil properties which will determine the water status of the ecosystems. In upland ecology, rice is grown under rainfed conditions, so the scope for improving yields through better water management is very limited but considerable scope exists for better utilization of rainwater for agricultural production through the establishment of simple water retention structures and technologies (Seck et al., 2012). Water management for inland valley crests intensification and diversification can be realized with residue management or mulching to conserve water and suppress weed. The construction along contour lines of small barriers with stones, tree stumps or deep-rooting graminae such as *Andropogon* spp. or *Chrysopogon zizanioides* (vetiver) to conserve rain water by infiltration and sedimentation of fine particles (silt and clay) can reduce erosion effects on slopping terrains and improve soil physical and chemical properties. In lowland, the most common way of improving the hydrologic characteristic of a field is bunding and constructing dams so that run-off is reduced and rainfall stored. (Becker and Johnson, 2001; Touré et al., 2009) have shown that bunding in rice increased rice grain yield by 40%, controlled weeds (25% less weed biomass than in unbunded plots) and increased N use efficiency as compared to unbunded plots. The other common action is to puddle (destroy soil structure) to reduce infiltration and deep percolation. This reduces water losses between one and four times, typically from 5-20 mm/day to 1-5 mm/day (Beets, 1990). In addition to water retention, puddling contributed in suppressing exiting weeds (Rao et al., 2007). Lack of water control can be an important constraint to lowland intensification (Kranjac-Berisavljevic et al., 2002; Sakurai, 2002). But in terms of land development (bunds and irrigation canals construction, flood control/water management) rice cultivation in lowland conditions may imply substantial investments.

Water management for dry season early maturing vegetable crops in inland valleys will rely mainly on the residual moisture towards the end of the wet season. For other dry season vegetable crops, irrigation is the most efficient way with drainage facilities in the field because most vegetables cannot tolerate prolonged waterlogged conditions. Ridges and mounds are also used for vegetable crops production in heavy inland valley soils to avoid waterlogging and to lessen weed pressure by burying weeds and their seeds in the mounds (Akobundu, 1987).

2.10. Soil fertility management

In the rainfed lowlands to intensified-lowland continuum, chemical fertilizers along with water availability and improved varieties have played a major role in increasing rice production. In West Africa rice agro ecologies, the main yield-limiting factors are nutrients deficiencies and weed infestation, particularly in non-irrigated fields (Seck et al., 2012). Study of Sahrawat et al. (2001) have shown that nitrogen (N) and phosphorus (P) are the most deficient soil nutrients for upland rice production in the humid forest agro ecological zone (AEZ). In the moist savannah AEZ, N is the most limiting factor, while P is moderately to slightly deficient. In both humid forest and savannah AEZs, potassium (K) is the limiting factor after three years of continuous rice production without fertilization. In the semi-arid zone, all macronutrients (N, P, K) have been found to be highly deficient. Overall, nitrogen is the most important factor, because N-demands of rice are high and losses from the field are high trough denitrification, volatilisation and leaching (Windmeijer and Andriesse, 1993). But over the years, fertilizer efficiency has tended to decrease because efficiency decreases as fertilizer rates increases, but also because soils deteriorate; and finally leading to a non sustainable system. Diversifications of cropping systems with cultivation of legumes or green manures, vegetables and root crops were developed to improve fertilizer efficiency, and add nutrients through the implementation of improved fallow (Bognonkpe and Becker, 2000). Another sustainable way of improving fertilizer efficiency can be through more balance chemical fertilization and better application techniques. Study of Oikeh et al. (2008) showed that by capturing mineral N flush and with moderate N and P, yield of interspecific rice varieties was substantially increased. Concerning fertilizers application techniques, N-loss was minimal with 20-80% efficiency increase when urea was incorporated as compared to the common farmers’ broadcast methods (IRRI, 2002).

2.11. Weed management

Weed control does not constitute major constraints as long as there is plenty of labor to hand weed or uses tools (hoe, machete...) to remove weeds. The problems start with the intensification of cropping systems when cultivated areas are expanded and fallows get shorter. To achieve substantial rice yield increase, it is necessary to develop different integrated weed control measures ranging from hand weeding, uses of herbicides, crop rotations, water management to the use of competitive rice varieties, timing of weed control, etc.

2.11.1. Direct weed control

2.11.1.1. Physical control

Hand pulling and uses of tools (hoes, small spades and scythe) are major means to control weeds in many small scales farms in West Africa. Although safe for the environment, this method is very time-consuming and labour requirements are estimated at approximately 50 person-days ha^{-1} (Johnson, 1997). For rice, efficient weeding should be done early in the crop's life at about 20 days after sowing (Touré et al., 2013); but most often weeding is delayed due to labour pressure at the beginning of the rainy season, when land preparation, planting and weeding all compete for the farmer's limited labour. Hand weeding is relatively ineffective in controlling perennials weeds which propagates underground with rhizomes and tubers. Confusion between rice plants and other resembling grasses such as *Echinochloa* spp. can mislead workers to remove rice instead of weeds (Moody and Cordova, 1985). As long as labor is available, this method is largely practiced, but when there is labor shortage, herbicide uses become popular.

2.11.1.2. Chemical control

In West Africa rice ecosystems, herbicides uses are common in intensified irrigation lowlands and in upland rice grown in rotation with cotton, and most of those herbicides is selectivity dependent (Johnson and Adesina, 1993). Selective herbicides comprise post-emergence herbicides which are applied after the weeds and rice have emerged, when weeds are at seedling stages; and pre-emergence herbicides are applied before the weeds emerge. Non–selective herbicides such as paraquat (contact) and glyphosate (systemic) are used in land preparation before rice seeding to suppress weeds which resist to selective herbicides. However, intensive and repeated uses of herbicides can be detrimental to the environment and some weeds can develop herbicide resistance (Lemerle et al., 2001). And most of all, the costs involved with herbicide constitute the major constrains to its wide adoption.

2.11.1.3. Biological control

Biological control measures concern the uses of animals, insects, or pathogens as weed suppressive agents, but doing no harm to rice or other crops. This method has been tried in very intensive irrigated rice fields with pisciculture (fish rising) and duck feeding to allow fish and duck to feed on weeds in few countries in Asia (Shibayama, 1992). However, this system requiring skills and more elaborate irrigated fields are not widespread in tropical smallholder fields in West Africa.

2.11.2. Indirect weed control

2.11.2.1. Land preparation

In inland valley rice based systems, straw or vegetation residue may be incorporated during land preparation. Fire and cultivation usually suppress most annual weeds, though perennial weeds with rhizomes and tubers may resist (Johnson, 1997). Although the following practices are not commonly applied in West African inland valleys, good tillage, puddling and land levelling can (1) further remove weed vegetation at seeding and suppress perennial weeds; (2) provide fine soil to allow uniform and early crop establishment; (3) permit uniform and easy irrigation and drainage (De Datta and Baltazar, 1996).

2.11.2.2. Crop rotation

Except fully irrigated rice systems in certain cases, continuous monocropping leads to severe weeds pest problems, and ultimately leads to decline of rice yields (George et al., 2002). Thus, rotating cereal crops such as rice with other broadleaves crops (grain legumes or vegetables) trough diversification can alleviate weed problems. And study revealed that leguminous cover crops enhanced rice productivity and even suppressed weed growth under intensified land-use systems in West Africa (Becker and Johnson, 1999b). It should be noted that many traditional smallholder farming systems in West Africa, practice sustainable crop diversification schemes with cereals such as rice, maize or finger millet, rotating with groundnuts, beans and cassava. In recent times, due to pressure on land, farmers have started to abandon crop rotations and practice monocultures and its correlated weeds and pests problems.

2.11.2.3. Water control

In the irrigated lowland where rice is most often transplanted, flooding can suppress most of the weed flora comprising upland and semi-aquatic weeds if there are perfect water control structures and sufficient irrigation water and levelled fields. For aquatic weeds and the others, farmers can afford chemical measures to control weeds. Thus, in irrigated lowland systems, weed constraints are less of a problem, factor contributing to the sustainability of this system (De Datta and Baltazar, 1996). However in the uplands and in the rainfed lowlands of the inland valleys, where rice is direct seeded, flooding is delayed until the crop is established, thus weeds and rice germinate simultaneously. Hence weeds are the major constraints in these rice ecologies, with yield losses ranging from 30 to 98% (Oerke and Dehne, 2004).

2.11.2.4. Fertilizer management

In this inland valley ecologies characterized by profuse weed growth, fertilizer management should be directed to rice crops only, and not to the weeds; meaning that weeds must be removed before nitrogen and other chemicals are applied. By failing to do so, leads to luxuriant weed growth, and rice yield would be lower than when there was no N application, because weeds have greater ability to compete much better for nutrients, water and light (Ampong-Nyarko and De Datta, 1989). Also deep incorporation (10 cm) of N fertilization in irrigated rice has improved rice yield and competitiveness against weeds (De Datta, 1981).

2.11.2.5. Fallow period and management

Major underlying reasons in shifting cultivation of field abandonment for fallow are the weed infestation and soil fertility exhaustion (Sanchez, 1976). Because during long fallow more than 6 years, the growth of woody species shades out many weeds preventing seed production and a build-up of populations (Johnson, 1997). Akanvou et al. (2000) showed that improved residue management tended to better control weeds than natural fallow.

2.11.2.6. Mulching

This is very effective in controlling weeds. If natural organic mulches are used, they help conserve moisture and add organic matter to the soil when they decay. The limitation of this method is the unavailability of large quantity of mulching materials for intensive large farms. Thus most of the times, mulching uses are limited to high-value crops such as some vegetables.

2.11.2.7. Cover crops and micro-organisms

Cover crops uses in inland valleys respond to two main priorities: weed suppression by shading out noxious weeds, and increasing soil-N content and N-supply to the crops through biological N fixation from the air (Beets, 1990). Promising micro-organisms and cover crops have been tested to fulfil those priorities; they comprise mainly micro-organisms (blue-green algae and azolla), green manures (fast- growing, aquatic and stem-nodulating shrubs from West Africa *Sesbania rostrata* and *Aeschynomene afraspera*) and cowpea (Becker et al., 1997). But except cowpea, the adoption of the other cover crops by farmers was limited, because farmers in West Africa are reluctant to adopt legume cover crops that are not for human consumption or without a direct economic benefit (Oikeh et al., 2008; Vanlauwe et al., 2001).

2.11.2.8. Crop establishment, interrow spacing and seeding rate

In irrigated and lowland systems, transplanted rice has two–to three-weeks head start over weeds, and that factor combined with water submergence allow transplanted rice crop to compete better against weeds, as compared to direct seeded rice. But in areas with acute labour shortage, transplanting has become very difficult and there is an increasing trend in favour of direct seeding culture. But the major problem with direct seeding characterized by the lack of head start and the absence of submergence of floodwater is the competition against weeds as weeds and rice germinate simultaneously. And when direct seeding is practiced consecutively, gramineous weeds become luxuriant (Johnson, 1997). In transplanted or direct seeding systems, increasing the plant population density through the use of higher seed rates and closer spacing can make the rice crop more competitive with weeds (Tosh et al., 1981). Similar results were found by (Akobundu and Ahissou, 1985) who showed that all rice cultivars competed better with weeds when grown at 15 and 30 cm interrow spacing than at wider spacing of 45 cm.

2.11.2.9. Weed prevention

This method involves to keep the farm clean and ensuring that a minimum of weed seeds is allowed to be added to the seed bank of the soil. It means to use weed-free seeds, clean borders, irrigation canals and farm equipment such as threshers to prevent weed seeds transfer from field to field (De Datta and Baltazar, 1996). Unfortunately, to most tropical smallholders weeding without it benefiting a standing crop is an alien idea indeed.

2.11.2.10. Rice cultivar

The choice of the rice variety may influence the competitiveness of the crop with weeds. And studies in the late 60’s and 70’s have shown that traditional rice varieties which are tall (rapid vegetative growth), have droopy lower leaves during early growth stages, vigorous leaf area development and high tillering capacity, are known to compete better with weeds, but yielded less when compared to improved and short statured rice varieties who lack the characteristics of the traditional varieties (Jennings and Aquino, 1968; Jennings and Herrera, 1968; Jennings and Jesus Jr, 1968; Kawano et al., 1974). But in recent studies, improved competitive rice varieties could be obtained without lowering yields or the trade-off mechanism (Fofana and Rauber, 2000; Gibson et al., 2003; Haefele et al., 2004; Ni et al., 2000). Detailed studies have also attempted to identify plants traits responsible for superior competitive ability of improved rice cultivars against weeds, including height, leaf canopy, tillering ability and root development (De Vida et al., 2006; Dingkuhn et al., 1999; Gibson et al., 2003; Johnson, 1996; Johnson et al., 1998; Jones et al., 1996; Jones et al., 1997; Koarai and Morita, 2003; Zhao et al., 2006).

2.12. Timing of weed control

Usually the sooner the weeds are removed, the better. It is good to have the plot without weeds all the time, but this may not be economical. Economic advantage is the idea behind the concept of critical period of weed competition. Undoubtedly, the longer the weed competes with the crop, the greater their effect will be. However, this effect is negligible until the environmental resources (air, water, nutrients) ceases to meet the needs of both the crop and the weed. Control is needed at the critical period when the demands of both types of plants cannot be met. Generally, the term critical period refers to the maximum period weeds can be tolerated without affecting crop yield, and this concept was verified by Nieto et al. (1968). The critical weed-competition period for lowland rice in Senegal was between 29 and 32 days after seeding (DAS) during the rainy season and between 4 and 83 DAS during the dry season (Johnson et al., 2004). For most vegetables crops (tomato, okra, pepper and some leafy vegetables), it is at the first third of the crop cycle or the first 42 DAS (Akobundu, 1987). To reduce the critical weed-free period, rice and vegetables are transplanted to give them an advantage over the weeds.

In light of all these weed control measures, an improved weed management system within the context of integrated weed management with emphasis on the use of weed competitive rice and vegetables cultivars is therefore needed for sustainable rice based production in smallholder farms in inland valleys of West Africa.

2.13. Effects of climate change on weed management in inland valley

Climate change is expected in the form of higher temperatures, raised CO_2 concentrations and changed rainfall patterns, and these will affect the survival and competitive ability of many weeds (Fuhrer, 2003; Ziska, 2007). Because of the biochemical and morphological differences among the three photosynthetic pathways (C_3 Calvin-cycle types (C_3 weeds), C_4-dicarboxylic acid types (C_4 plants) for the majority of plants and crassulacean acid pathway type (CAM) plants), each has its own unique set of advantages and disadvantages. These differences result in differential performance in different environments or ecologies. Increased temperatures and limited soil moisture conditions (drought) may favor the growth of C_4 species over C_3 species but will also affect the survival of some species and allow them to extend their range to more northerly or southerly latitudes (Fuhrer, 2003; Rodenburg et al., 2011). Furthermore, because of the likely tolerance to drought and heat, C_4 species are likely to become more competitive in inland valleys under the ever increasing influences of climate changes. These may include the perennial grasses *Imperata cylindrica*, *Paspalum scrobiculatum* and *Cynodon dactylon*, the annual grasses *Rottboellia cochinchinensis*, *Digitaria horizontalis*, *Dactyloctenium aegyptium*, *Pennisetum purpureum*, *Echinochloa colona* and the sedges *Fimbristylis littoralis*, *Cyperus rotundus* and *Cyperus esculentus*. These weeds could be controlled through integrated approaches that combine preventive and curative measures (Rodenburg et al., 2011).

Chapter 3

Context, justification, approach, concepts and methodology of the research

3.1. Context of the research

Between 1991 and 2011, rice production in different rice growing agro-ecologies in sub-Saharan Africa remained stagnant or increased slightly from 5Mt to 14Mt, while it increased approximately more than 3 times in Asia (AfricaRice, 2011). This stagnant trend in these agro-ecologies are due to numerous constraints, and West African inland valleys farming systems seek to adapt their current practices to the constraints ignited from a growing population. At the beginning in the former and stable phase, more land is put under cultivation with less population (Elmquist et al., 2003). Then, in the vulnerability scenario (Figure 8) with more population, and land becoming scarcer, there are various ways out: shortening the fallow period, prolonging the cultivation period, cultivating marginal sites, and adapting the cropping practices. Under traditional non intensified farming system, one crop of rice is grown per year because swamps are not developed and water flow is not controlled (AfricaRice, 2011). In some inland valleys through West Africa, due to the promotion of small scale agricultural lowland by development projects and NGO's, intensification and diversification practices are frequently observed in lowlands. Intensification is related to water control management where upstream pond and irrigation canals or canals to prevent flooding are built (Singbo and Oude Lansink, 2010). Among the ways to intensify and diversify these inland valleys systems, one is to use the irrigation scheme or residual moisture, which is frequently available after rice harvest, for rice double or triple cropping or for off-season vegetables (Balasubramanian et al., 2007).

Concerning the intensified and diversified systems in West African inland valleys, there has been little work on studying the natural resources management on an encompassing cropping season scale integrating the main rainy season rice crop and the off season cereals (corn rice, sorghum, etc.) and vegetables. Because, it is expected that intensified cultivation on heterogeneous extended slope uses of the catena with spatial gradient will lead to scarcity of water, nutrient depletion in the soil, and weed infestation. A generally observed feature is that the former system functioned with apparently satisfactory yields, good regeneration of forests or savanna, and few weeds, and that the new vulnerability scenario in intensified system has declining yields, poor regeneration and many weeds (Elmquist et al., 2003). In West African inland valleys rice ecosystem with relatively high rainfall and temperatures, losses due to weeds are more severe than those caused by nitrogen deficiency, pests, or diseases (AfricaRice, 2011). Furthermore, relative maximum yield losses due to weeds may range from 28-74% in transplanted lowland rice and 28-89% in direct seeded lowland rice (Johnson et al., 2004; Rodenburg and Johnson, 2009) . Unlike in irrigated lowland rice systems, transplanting is not a common practice in inland valley agroecosystem because of the absence of flood water. In irrigated systems, rice has a two- to three-week ‘head start’ over weeds, which favors rice in competition against weeds. Whereas in inland valley cropping systems with no water control (the hydrological regime is strongly influenced by the rainfall), rice crop is generally sown directly in no puddled and no flooded soil, where weeds and rice germinate simultaneously, bringing more severe weed problems in these moist and hot conditions. High weed-inflicted yield losses in rice in West Africa are mainly due to the limited number of effective and affordable weed control options available to farmers (Rodenburg and Johnson, 2009). Hand weeding is the method most used by farmers, and herbicides uses are limited (Adesina et al., 1994). In practice, manual weeding requires considerable labor between 205-780 man h ha^{-1}, and the cropping calendar has to be organized such that peak working times do not occur simultaneously for different crops in the sequence (Beets, 1990). Herbicides treatments offer substantial time and labor gains, and increased crops yields of more than 300 and 450 kg ha^{-1} in Cote d'Ivoire and Benin respectively when compared to traditional weed control without herbicide in cotton crop fields (Marnotte, 1997). But the uses of herbicides present special problems because of their limited availability and cost, and the low level of farmer literacy (Rodenburg and Johnson, 2009). Furthermore, to aggravate weed management problems, study showed that weeds vary during the crop season with the ecological conditions (Barralis and Chadœuf, 1980). Thus most of West African inland valleys are passing through a period in which they have become unproductive, ecologically damaging farming systems. The ultimate goal of the stakeholders (farmers, extensions agents, developers, scientists…) is to explore the feasibility of increasing its yield per unit land and of making it sustainable with fewer inputs.

Then research was carried out in two periods between 1997 and 1998 in Cote d'Ivoire and between 2010 and 2011 in Benin. Although the research studies were conducted at different period of time and in different countries, a common thread between the two studies was woven with the prominent role of the heterogeneity on the catena (agro-ecological gradient) in influencing the variability of the elements of the environment: weed communities, water and nutrient. The first period in Cote d'Ivoire was part of activities of the Inland Valley Consortium (IVC). Research activities were focused on biophysical and socio-economic characterization studies on key sites, and on the development and evaluation of technologies for improved production systems and natural resources management. Specifically, the study focused mainly on water management along the heterogeneous catena of inland valley in Cote d'Ivoire. Further research was needed to analyze the weeds dynamics and management practices in another different agro-ecological zone such as Benin with different productions units and cropping systems scattered along the heterogeneous catena of inland valley in Benin. Hence for the second period, the research was carried out between 2010 to 2011 as part of the trans-disciplinary research programme of the project RAP (Realizing the agricultural potential of inland valley lowlands in sub-Saharan Africa while maintaining their environmental services) which is an output of the inland valley consortium (IVC) research program hosted by the Africa Rice Center (AfricaRice). The objective of that project was to enhance the productivity and competitiveness of inland valley lowlands through sustainable intensification and diversification of agricultural productivity and product value chain development, while conserving land and water resources. The disciplines integrated in this project were agronomy, weed science, soil science, social science, Geographic Information Systems (GIS), and water management.

3.2. Research approach and rationale

Our research is part of a scientific approach in agronomy in term of combining a comprehensive analysis of the technical practices, their assessments and the design of new ones (Boiffin et al., 2001). To address the issue of implementation of a technical change in the farming systems, we chose to combine the analysis of farmers' weed management practices in inland valleys with the assessment of the effects of the agronomic management on the evolution of the weed flora and yield of rice. This dual approach is justified taking into account:

- the characteristic of the farming systems involving complex decision situations regarding the weed management on the heterogeneous catena,

- the lack of references agronomic references both on the weed management and agronomic management on the functioning of the inland valley agro-ecosystem,
- the need to produce these two forms of agronomic knowledge for the development of a diversified guidance for the development of good agricultural practices leading towards sustainable production systems in West African inland valleys.

The main objective of this research is to provide elements of characterization of weed management situations and technical references on the effect of agronomic management in inland valley (Figures 11 and 12). These tools to the use of agricultural and extension agents can be used as a support for discussion with the farmers on the merits of lowland development and the benefits they can expect. Two levels of analysis are necessary to develop these tools:

(1) The entry point is the general presentation of inland valley of across West Africa. This characterization is supplemented by a presentation at the farm level of weed management practices followed during two years in three inland valleys in Benin. This first approach allows a general statement of the problem faced by rice and vegetables in inland valleys, and highlights the major constraints faced by farmers in their specific situations (Papy, 2004). It aims in particular to identify weed management problems in the farming system and the way in which farmers are trying to circumvent them along the heterogeneous catena.

(2) Using the heterogeneous catena as a methodological tool, the last level of analysis at the level of experimental plot, focuses on the assessment of the effects of the agronomic management in inland valleys in Cote d'Ivoire. This step is valued *ex ante* for finer investigation along the heterogeneous catena of the agronomic management effect on weed infestation, water control and mineral fertilizer uses. A technical experiment focused on water management must allow to precisely test the hypotheses about the advantages and disadvantages offered by the

agronomic management (mainly weed management) for a range of environments representative of the diversity of cropping systems along the heterogeneous catena. The results will increase the costs and the benefits of innovation, *in fine* to enrich discussions between developers, extension agents and farmers and to achieve a sound integration of the lowland development in the technical itinerary.

Analysis level	**Study object**	**Methods**	**Expected results**
Farm	Conception, organization and management of weed problems in inland valleys Crops (rice and vegetables) and weeds population in inland valleys	Surveys Interviews Field observations Bibliography	Unraveling farmers' indigenous knowledge and decisions on weeds Constraints encountered
			Farmers' strategies of increasing the productivity of inland valley rice based systems
Plot	Cultivated rice and vegetables fields on catena in inland valleys Weed development Farmers' weed management along the catena in inland valleys	Surveys Field observations Agronomic diagnostic with yield measurement	Technical references on the effects of agro-ecological weed management in inland valleys systems on yield variability

Figure 11. Diagram of the research approach, levels of analysis and expected results for Benin.

Analysis level	Study object	Methods	Expected results
Plot	Cultivated rice fields on catena in inland valley Water, nutrients and weeds on catena in inland valley	Field observations Experimental trials	Technical references on the effects of agro-ecological management of water, nutrients, and weed in diverse inland valleys systems on yield variability

Figure 12. Diagram of the research approach, levels of analysis and expected results for Cote d'Ivoire.

The systemic approach was retained in the study in order to explain weed infestations and related yield declines by taking into account agricultural practices in combination with environmental factors as climate, vegetation and soil, and social and economic factors. The systemic approach is a more synthetic than analytical in distinguishing the properties of dynamic interactions between group elements, conferring it a holistic character (Brossier, 1987).

The next approach used trans-disciplinary stand in order to merge agronomy with ecology as recommended by modern schools of thought (Deléage, 1991). This approach combined agronomy with focus on agricultural management and ecology, especially the interactions among biological components at the group of fields or agroecosystem level. And the key concept of agroecosystems was defined as the intervention of human activities (cropping systems) on the ecosystems[1] (Blandin, 1992; Wezel et al., 2009).

And specifically for inland valleys where the study took place, the geomorphology and hydrology are mainly characterized by the catena ranging from the fringe to the valley bottom (Andriesse and Fresco, 1991). The catena is in itself a landscape concept describing an environment in which a diversity of ecosystems occurs. The crests/valley bottom catena refers to a sequence of land types and associated ecosystems located along the slopes of the local topography. The ecosystems on the catena vary from the crests on the highest parts, through hydromorphic conditions lower down the slopes, to center of the valley bottoms. Key parameters of soil and water, which determine the potential for cultivation, are closely related to the location on the catena (Andriesse and Fresco, 1991). Different parts of these catenas have their own physical constraints (weeds, hydrology, drought, low soil fertility, etc) and socio-economic

[1] Ecosystem is an association of living organisms and its geological, pedelogical and atmospheric environment. The constituting elements of an ecosystem develop a close network of dependability allowing the development and maintenance of life.

constraints (Figure 13). Then agroecology emerged as a distinct conceptual framework with holistic methods for the study of agroecosystems. Therefore, agroecological characterization describes climatic, hydrologic, and edaphic factors, but also demographic patterns, systems of land and labour organization, market infrastructure, health risks, and other factors that can influence sustainably the cropping systems actually applied by farmers in any given physical setting (Altieri et al., 2012; Gliessman, 1997).

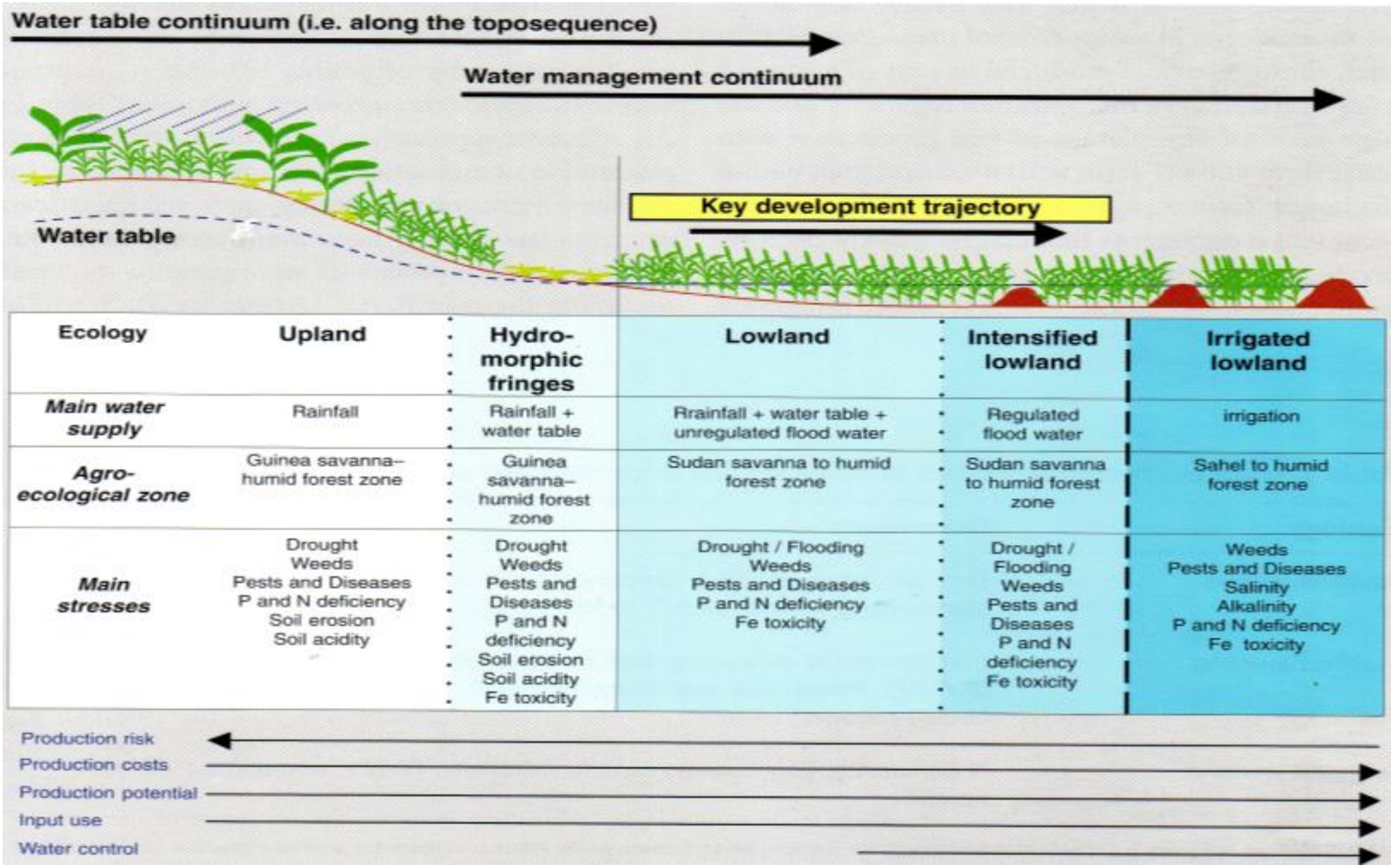


Figure 13. Conceptual model of catena and intensification continua of rice-growing ecologies (AfricaRice, 2011).

3.3. Common conceptual frame for the research studies

3.3.1. Concepts of farming systems and practices used in the studies

Earlier, farming system refers to a portion of an area cultivated with the same method (Sebillotte, 1974). To distinguish this definition of the agroecosystem formed by a set of plots, the statement was slightly changed, and farming system meant as the entire technical operations implemented on homogeneous treated plots. Each farming system is defined by (1) the nature of the crops and sequencing, (2) cropping patterns applied to these crops which includes the choice of varieties for selected crops (Sebillotte, 1990). The cropping pattern is a combination of logical and orderly cultivation techniques (Sebillotte, 1974). The farming system can be applied not only to a plot, but also to a group of plots or a block of crops[2] (Meynard et al., 2001). It takes into account different time step in the cropping cycle and sequencing. Thus defined, farming systems vary greatly around the tropics, from monocropping to complex mixed associated systems (Boiffin et al., 2001). The position of the concept, defined on a portion of territory, is based on the assumption that the cropping actions are coordinated between them because of the relationship between techniques, cultivated plant stand and environment (Papy, 2001). The study of these relationships allows achieving a diagnosis of efficiency of the farming system and designing new ways of cultivating field.

3.3.2. The evaluation of practices for the improvement of farming systems

The effectiveness of farmers' farming systems (agricultural practices) can affect crop yield (influence of various environmental conditions, insufficient or irregular productivity, effect of a change in cultivation technique), but also the quality of the products or the environmental effects

[2] The term farming system is slightly different from cropping systems which are subsystems of the farming system constituting land use unit where the nature of the crop sequencing and the terms of controlling the production are rather homogeneous.

of the farming system (Kropff et al., 2001). This area of agricultural research seeks to understand the functioning of the cultivated ecosystem, i.e. the relationship between environment and cultivated crops under the effect of practices (Jouve, 1990). The agronomic diagnosis is one of the main tools for the evaluation of practices, from the analysis of the yield components, to identify the characteristics of the environment and the farming system having influenced the production (Doré et al., 2008). This method can be used at the regional level to identify and prioritize the responsible technical acts of an agricultural problem in a region (Doré et al., 1997). Indeed, the definition of the priorities of research across a formulation of problems based solely on elements discussed with farmers and experts remains generally insufficient and leads hardly to consensus (Smith, 1994). In view of the complexity of the climate/soil/plant relationships and many interactions between cultivation techniques at the level of a farming system, the risk of confusion of effects are important. Thus the identification of the real causes of the problems requires observations and measurements in a network of plots (Doré et al., 1997).

This method is applicable in the context of tropical peasant agriculture, taking care to identify agro-ecological and social specificities. In tropical Africa, there is a significant heterogeneity of the physical and biological environment in the same plot (termite mounds, topographic accident, tree stumps), plus a great variability of the cropping patterns linked to manual cultivation and diversity of workers (Jouve, 1990). In view of the slow pace of cultivation operations, a plot consists of multiple subplots (area treated evenly) characteristics of well specified cropping cases (Milleville and Serpantié, 1991). It is at this level that one can be assured of homogeneity of environmental conditions and applied cultivation techniques. The diagnosis must be done from a sample reasoned with cropping situations taking into account the variability of the environment studied at higher scales (agricultural region, village, farming system), and using assumptions about the causes of variation in yields resulting from exploratory surveys and observations on cropping practices.

The diagnosis is part of the process of improving the farming system leading to the development of innovative farming systems. The main objective is to define new ways of reasoning cropping patterns with their area of validity (Meynard et al., 2001). A widely developed approach is to use the modeling of the functioning of the agroecosystem, to predict the effects of cropping systems and thus quickly determine, by exploring different scenarios, the systems capable to achieve farmers' goals (Jones et al., 2003; McCown, 2002). Thus farming system is evolving towards a concept of decision making unit and a land use system based on agriculture.

3.3.3. Analysis of the decision making process for technical management of a crop

The analysis of cultural practices, from the point of view of farmers, is a preferred means to reveal the diversity of cropping patterns, goals and strategies set by producers, specific constraints they face, by taking into account the available tools and the social organization of labour (Jouve, 1997). Much work has been done recently on the decision processes that determine farmers' practices (Papy, 2004). It has been shown not only that farmers plan cyclical and repetitive technical operations but also that this planning can be modelled (Sebillotte and Soler, 1990). Some studies describe how modelling decision processes allow explaining farming practices and comparing achievements between different farmers in the same year or between years for the same farmer, or the introduction of technical innovation (Aubry and Michel-Dounias, 2006). The concept of farming system limited at the plot level is here placed at the level of the functioning of the production unit, but also at more inclusive levels as the village or region (agricultural policies, market of agricultural products) where some determinants of chosen technical options can be located (Jouve, 1992). The African situation studies emphasize the particularity of the concept of production unit (PU), understood here as a family PU, with a nuclear or extended family (the household or PU head, wife or wives, one or several offspring), which may require the identification of different levels of decision, even if the family group depends on the PU head who makes the main choice for the organization of daily activities (Dounias et al., 2002). In this case, it is necessary to integrate the social aspect of production to the analysis of the cultivation practices and underlying factors.

According to Köbrich et al. (2003b), each agricultural household is unique in terms of labor force, management skills and capital. This implies that any agricultural household and agricultural system is different if not unique, facing distinct problems of decision-making and of technical management, and whose solution would also be unique (Köbrich et al., 2003b). At the scale of the household, opportunities for access to productive resources (bio-physical resources and socio-economic conditions) largely determine the diversity of agricultural exploitations and the variability of cropping systems (Dogliotti et al., 2006; Iiyama et al., 2008; Tittonell et al., 2005b). Thus farmers develop different strategies following the opportunities and the specific constraints faced in their environments. At a regional level, the agro-ecological conditions, the opportunities for market access, the population density determine the variability of production systems (Erenstein, 2006a; Jansen et al., 2006; Tittonell et al., 2005a). The strategies of farmers to deal with the accessibility to productive resources (land, labor force, financial resources...) are not only confined to alternative methods of management of farms but also to off-farm activities (Blazy et al., 2009; Joffre and Bosma, 2009; Tittonell et al., 2010b; Valbuena et al., 2008b). In some West African countries, these off-farm activities may comprise motorcycle taxi transport in the cities, trading with selling fuel on the black market, and distilling palm wine into popular, local liquor. These off-farm strategies may also influence the conduct of cropping systems. Thus technological interventions or management for improved productivity must take into account this diversity of systems and the farmers' responses in a systemic approach.

Thus it is necessary taking into account the diversity of farming systems by developing a typology of agricultural systems.

3.3.4. Typology of agricultural systems

The main objectives of the typology of agricultural systems are: (1) to describe and structure a farm sample taking into account the diversity; (2) to show a maximum homogeneity within particular types while obtaining maximum homogeneity within particular types (Köbrich et al., 2003a); (3) to underline linkages between different indicators and underlying drivers (Andersen et al., 2007); (4) to simplify the diversity of farmers and farming strategies. The typology is an artificial way to define different groups based on specific criteria in order to organize and analyze reality (Valbuena et al., 2008a).

Different methods to construct typologies have been described (Köbrich et al., 2003b; Landais, 1998). For example, a typology can be constructed using qualitative or quantitative analyses; attitudinal or socioeconomic variables; and scientist knowledge or participatory processes. The choice of a particular analysis depends on the selected criteria and the available data (Valbuena et al., 2008a). For quantitative methods also called positivist method (Blazy et al., 2009; Iraizoz et al., 2007; Köbrich et al., 2003a; Maton et al., 2005; Poussin et al., 2008; Tittonell et al., 2010a) and qualitative method also called *a priori* approach or constructivist method (Andersen et al., 2007; Dalgaard et al., 2006; Daskalopoulou and Petrou, 2002), factor analysis is used to reduce the number of variables and thus the 'dimensionality' of the problem (Köbrich et al., 2003a). It defines the underlying structure in a data matrix, analyzing the nature of interrelationships among a typically large number of variables by defining a set of common underlying dimensions factors (Iraizoz et al., 2007). Principal Component Analysis [PCA] can be used for quantitative variables and Multiple Correspondences Analysis [MCA] (Tenenhaus and Young, 1985) for qualitative variables (Blazy et al., 2009; Iraizoz et al., 2007). Then, determining how many factors should be retained is a problem, as with real data the actual number that merit retention is often considerably smaller than the number of variables (Köbrich et al., 2003a). The number of factors from the PCA or MCA to be included in the cluster analysis can be based on the criterion known as ‘‘rule of the elbow’’ when checking the Eigen values (Maton et al., 2005).

Individual farms are then grouped into farm types using an Agglomerative Hierarchical Clustering (AHC) algorithm, in which the principal components of the PCA (or of the MCA) are used as input variables (Blazy et al., 2009). Cluster analysis is used to classify the observations according to m-variables of an n-dimensional attribute space (Köbrich et al., 2003a). At each step, the algorithm groups individuals into pairs by selecting the individuals with minimum dissimilarity (Blazy et al., 2009).

Once the cluster sequence has been established where the process will be cut and thus how many clusters will be defined can be determined. The pairs thus obtained can be then aggregated using Ward's minimum-variance method (Blazy et al., 2009; Iraizoz et al., 2007; Poussin et al., 2008). This method progressively aggregates individuals by minimizing the augmentation of the total intra-class inertia. The advantage of this method is that it produces very homogenous classes, which is useful for the readability of the typology in the second step of the methodological framework. Otherwise, expertise can be used to determine the number of classes from the hierarchical tree (Maton et al., 2005). The hierarchical tree (dendrogram) can be cut through subjective inspection or, more formally, by plotting the number of clusters against the change in the fusion coefficient (i.e. the difference between the distance coefficient at one clustering stage and the previous one) (Köbrich et al., 2003a).

Practically in Benin inland valleys, the aims were to combine two *a priori* typologies: (1) a typology of lowland rice-based farmers determining bio-physical and socio-economic of the production units with (2) a typology of cropping systems that determine the diversity of cultural practices and the decisions making processes linked to those practices (Michels, 2005; Michels et al., 2009). Thus the general approach integrates two scales of analysis (Figure 13).

At the scale of farmers or systems of activities, the study sought to understand the organization of activities in time and space, the place of agriculture in their activities, the importance and the place of the activities in the lowlands, the opportunities for access to productive resources and their allocation. This analysis provided information on the overall operation of farms in these areas and on bio-physical and socio-economic contexts in which were developed the activities of lowlands development and the strategies adopted by the farmers.

At the scale of rice and vegetable farms or lowland cropping systems, the study sought to understand the place and the importance of different crops (rice and vegetables), the rotations, the location of these crops in times and their integration. This scale also sought to provide information on the decision-making variables of cropping systems (farmers' goals-income, food preferences, risk, resources constraints, land labor, capital, etc.) and the main determinants of agricultural practices.

For small-scale farmers, agricultural practices are sometimes influenced by off-farm employment which can often provide some part of the cash income for the household. There is, however, a danger that some farmers seek for the more lucrative off-farm activities which then results in a shortage of labour on the farm and a deterioration of its productivity. This has been a problem in many parts of tropical Africa, especially in stones mining area of our study sites. The combination of off-farm employment and farming activities leads to the concept of activity systems and pluriactivity.

3.3.5. Activity systems and pluriactivity

The concept of system activity was developed as a result of the confrontation of production systems with more complex situations particularly in developing countries (Paul et al., 1994). Chayanov (1990) proposed an organizational plan, which included the main features of the production system and the issue of off-farm activities. The production system has been considered as the field of coherence of the rationality and planning of the farmer (Brossier, 1987; Paul et al., 1994). This concept has lost its heuristic value in developing countries where more complex and diverse situations prevail. In these countries, family farm decision-making exceed the farming activities and needed to be do understood in the light of broader strategies (Bida and Pluvinage, 2006; Chia et al., 2006; Dufumier, 2006; Paul et al., 1994). Therefore, it appeared that the logics that drive production systems and farmers can be well understood with reference to a meta –system encompassing other productive activities of the household (Paul et al., 1994). This meta-system is referred to activity systems. The concept of activity systems, pluriactivity and the functional relationships between the different activities and the various production units is applicable at the level of the whole household (Brossier, 1987; Dufumier, 2006; Paul et al., 1994).

Then pluriactivity intensity taking into account the number of activities and their schedule calendar in the year is defined below:

$$IPA_k = \sum_i^n \frac{m_i}{12} \qquad \text{Equation 1}$$

where IPA_k is the pluriactivity intensity of farmer k; m_i is the time period of the activity in number of months of the year; n is the number of activities of the farmer.

3.4. General methodology of the studies

In order to explore a diversity of farming systems, the sites in Benin and Cote d'Ivoire were selected in situations mainly characterized by the Guinea savanna zone ecology, the physical environment (catena gradient) and the importance of lowland rice in the production systems in the targeted West Africa inland valleys (Figure 14). The main research activities were descriptive and exploratory surveys and vegetation sampling, and field experiments. Surveys were used to characterize the major farming systems as well as cropping systems, to define the relevance of the inland valleys among the other cropping systems, and to examine the prevailing constraints. The surveys included interviews with farmers, observations of their cultivation practices and field measurements. The inland valleys vegetation and crops were sampled to monitor development in terms of weed suppression and weed management, and yield variations. Thus surveys were used to study the effects of cultivation practices on the weed infestation and on crop production in Benin. Information gained from the surveys and vegetation sampling was used to design *ex ante* the experiments in Cote d'Ivoire and to discuss the relevance of the results. For the experiments, the factors concentrated on rice yield variability, agricultural practices, production constraints, and testing technologies. The experiments were researcher-managed trials, laid down on fields rented from farmers with full farmers' participations in land preparation. The main preset criterion for the selection of these fields was the prevailing rice-growing agro-ecosystems in inland valleys with relatively high cropping intensity.

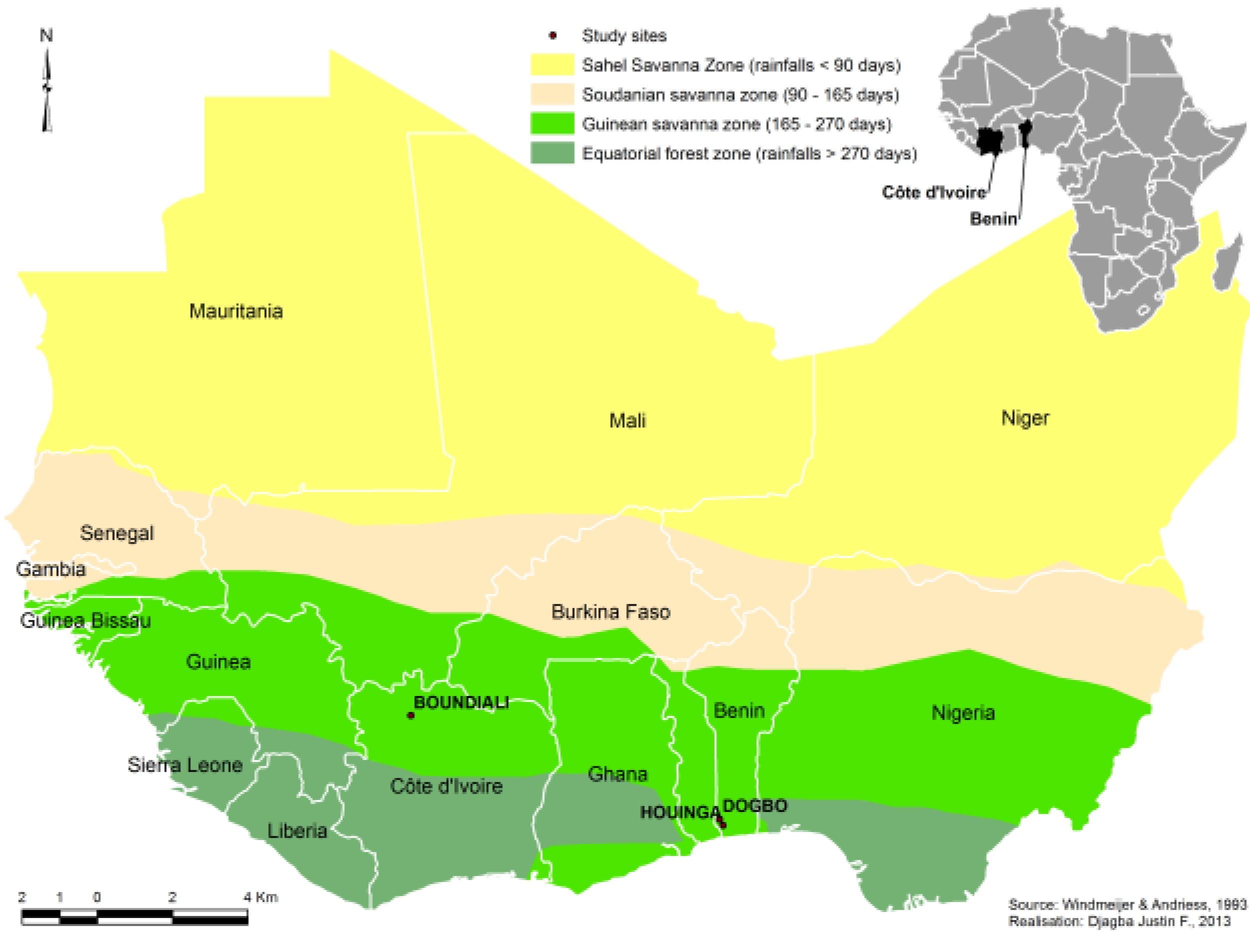


Figure 14. Locations of the study sites in Benin and Cote d'Ivoire along agroecological zones.

3.5. The study sites

3.5.1. Benin sites

3.5.1.1. Location and characteristics of the study areas

The study refers to the Mono Couffo regions in southwestern Benin and covers inland valleys in three villages (Agbedranfo, Vovokame and Houinga) (Figure 15). The Mono Couffo region borders the Atlantic Ocean in the South, the Togo republic in the West, and the departments of Zou and the Atlantic in the North and East respectively. The fields surveyed represented the major agro-ecological zones and were selected as follows. First, representative villages located near valleys and possessing farmers' organizations or multi stake holder platform (MSP) linked to RAP project were selected. Second, a stratified sampling method based on the heterogeneous catena was chosen: valley crests, hydromorphic fringe and valley bottom. Third, fields were selected regardless of size, and on the grounds of accessibility (adjacent to road) and whether it carried the required crop (rice) or crop combination (rice/vegetables). Overall, these valleys were selected based on agricultural potential for rice production, opportunities for crop diversification, variability of biophysical and socio-economic conditions in terms of climate, crops and farming systems, access to input and product markets, access to water and land, population density and the presence of others actors like NGOs (Non-Governmental Organizations) and development projects.

Figure 15. Map of the South Mono Couffo region of Benin and location of the study area.

The population of the mono Couffo region was estimated in 2007 at 1023000 inhabitants on an area of 4110 km^2, with a mean population density of 250 inhabitants/km^2, one of the highest in West Africa (PNE-Benin, 2009).

The hydro agricultural potential of the region is estimated at 27540 ha of irrigated land, and the lowlands composed of inland valleys, floodplains, and swamps cover approximately 20000 ha. But only around 10% of this lowland potential is actually used for agricultural production (PNE-Benin, 2009). The hydrological regimes of most of those lowlands are under the influence of rainfall, the inundation of the Mono and Couffo Rivers, and water from artesian wells. Although the region offers favorable water resources for better agricultural production, the production systems of the region are still subsistence oriented with low yields. Because of the demographic pressure with high population density, the traditional long fallow systems and individual fields' sizes have been reduced considerably, leading to the low agricultural productivity. And this population pressure with its subsequent low productivity led to the cultivation of marginal lands mostly located in the lowlands, triggering the diversified production systems with off season vegetables, lowland rice cultivation, extensive pisciculture, crafting, trading, and gravel mining. On upland ecology, staple crops are corn (*Zea mays*), cassava (*Manihot esculenta*), cowpea (*Vigna unguiculata*), and peanut (*Arachis hypogea*), whereas commercial crop such as cotton (*Gossypium hirsutum*) is becoming an increasing source of revenue for farmers. Generally in lowland during the off season, vegetables such as tomato (*Lycopersicon esculentum*), hot pepper (*Capsicum frutescens*), eggplant (*Solanum macrocarpon*), sweet corn (*Zea mays*) and jute mallow or crincrin (*Corchorus olitorius*) constitute the main crops.

In the Mono Couffo region, the increasing intensification and diversification are taking place mainly in the irrigated perimeter of some lowlands with the cultivation of lowland rice and vegetable crops during the rainy season and the dry season respectively.

A detailed characterization and dominant production systems in the study villages is presented in Table 2.

Table 2. Characterization of experimental sites and dominant production systems.

DEPARTMENT	Couffo	Couffo	Mono
MUNICIPALITY	Dogbo	Dogbo	Houeyogbé
VILLAGE/WATERSHED	Agbedranfo	Vovokame	Houinga
LOCATION			
Longitude(°)	1.72 E	1.75 E	1.82 E
Latitude (°)	6.76 N	6.79 N	6.59 N
CLIMATE			
Agro-ecological zone	Southern guinea savanna	Southern guinea savanna	Southern guinea savanna
Growing period (days)	225	225	240
Annual rainfall (mm)	950	950	1100
Rainfall distribution	Bimodal	Bimodal	Bimodal
PRODUCTION SYSTEM			
Tillage	Manual/tractor	Manual	Minimum tillage
Seeding methods for rice	Dibbling in lines	Dibbling in lines	Transplanting
Rice varieties	Improved	Improved	Improved
Seeding methods for vegetables	Broadcast/dibble/transplant	-	-
Vegetable varieties	Traditional	-	-
Intercrops	Okra/pepper	-	-
Rotation crops	Rice/vegetable	Rice/corn	-
Input use	Some NPK and urea	Some NPK and urea	Some NPK and urea
Irrigation	Artesian well	Artesian well	None
Production objective	Subsistence/sale	Subsistence/sale	Subsistence/sale
Mechanism of intensification	Crops cycles,+/-mechanization	Crops cycle	Use of inputs (herbicides)
Access to market [a]	Moderate	Good	Bad
Decision maker	Men/women	Men/women	Men/women
Land tenure	Inheritance, rented	Inheritance, purchased	Inheritance, purchased
REGIONAL IMPORTANCE			
Studied lowland area in ha	40	12	200
Share of inland valley area (%) in the region	0.2	0.1	1

[a] Market access is defined by distances from all-weather roads: good (not more than 2 km), moderate (not more than 5 km), bad (more than 5 km).

3.5.1.2. Geomorphology and soils

The dominating element of the coastal basin in which the Mono Couffo region is included is the major plateau. They are separated by large river streams; the Mono River forms the western boundary, the Couffo, Ouémé, and in the northern part the Zou River intersects the plateau from North to South. In East-West direction the plateau are separated by the central depression. The southern plateau is very even. They drop gently from their northern fringe (160 m NN) to the south (20-40 m NN) where they are bordered by a former erosive coastline and a level littoral belt that extends 4 - 10 km along the coast line. Medium slopes (4 – 8 % gradient) encircle the plateau and separate them from the central depression, the valleys and the littoral belt (Obemines, 1989).

According to Stahr et al. (1999), the following major soil associations can be observed in southwestern Benin. Acrisols developed on old and impoverished red parent material, and red soil on *Terre de barre* plateau. Topsoil texture is sandy while in the subsoil clay content increases. The soils are rather homogeneous and easily draining. No obstacles restrict rooting so they are appropriate for tree crops. Because the parent material is altered, the nutrient reserves are low and available nutrients mainly depend on the turnover of the organic matter. North-South flowing rivers cut large valleys and their alluvial soils are subject to seasonal floods. In inland valleys and lowlands running South-West to North-East between rows of *Terre de Barre* plateau, Vertisols develops mainly on marine marls. These soils are rich in nutrients but clayey, waterlogged and difficult to work.

3.5.1.3. Vegetation

Using the UNESCO (1973) world classification, Vooren (1985) has defined the natural vegetation as southern guinea savanna dense shrub trees which often coppice from their root stocks. The density of trees and number of trees species gradually decrease at a regional scale from South to North. The regional change is related to the rainfall gradient while the local change depends on soil moisture availability. More specifically for the study area, the vegetation derives from relics of remaining natural forest and guinea savanna, and its main feature is the overall presence of palm tree (*Elaeis guineensis*) in spontaneous or dense plantation form. In the inland valleys of the study area, the vegetation is mainly composed of grasses (*Digitaria horizontalis*, *Paspalum scrobiculatum*, *Leersia hexandra*, and *Echinochloa colona*), sedges (*Cyperus rotundus*, *C. sphacelatus*, *C. haspan*, and *C. distans*), and broadleaved species (*Ludwigia decurrens*, *L. octovalvis*, *Alternanthera sessilis*, *Eclipta prostrata*, and *Ipomea aquatica*).

3.5.1.4. Farming systems and cropping calendar according to agroecological zones

The crops and cropping calendars in the different agro-ecological zones are shown in Figure 16.

<table>
<tr><th>VILLAGES</th><th>AGROECOLOGICAL ZONES</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th></tr>
<tr><td rowspan="15">AGBEDRANNFO</td><td rowspan="5">DEVELOPED LOWLAND</td><td rowspan="5"></td><td colspan="6" rowspan="5">RICE</td><td colspan="6">OKRA + HOT PEPPER (round fruit)</td><td colspan="3"></td></tr>
<tr><td colspan="6">OKRA</td><td colspan="3"></td></tr>
<tr><td colspan="6">HOT PEPPER (round fruit)</td><td colspan="3"></td></tr>
<tr><td colspan="6">CORCHORUS</td><td colspan="3"></td></tr>
<tr><td></td><td colspan="5">SWEET CORN</td><td colspan="3"></td></tr>
<tr><td rowspan="3">NON DEVELOPED LOWLAND</td><td colspan="7" rowspan="3">INTERCROP OR CASSAVA OR CORN OR RICE</td><td colspan="8">OKRA + HOT PEPPER (round fruit)</td><td></td></tr>
<tr><td colspan="8">OKRA</td><td></td></tr>
<tr><td colspan="8">CORCHORUS</td><td></td></tr>
<tr><td rowspan="4">VERTISOL</td><td></td><td colspan="6">OKRA</td><td colspan="3"></td><td colspan="5" rowspan="4">CORN</td><td></td></tr>
<tr><td></td><td colspan="6">CORCHORUS</td><td colspan="3"></td><td></td></tr>
<tr><td></td><td colspan="6">HOT PEPPER (long fruit)</td><td colspan="3"></td><td></td></tr>
<tr><td colspan="2"></td><td colspan="5">CORN</td><td colspan="3"></td><td></td></tr>
<tr><td rowspan="3">FERRUGINOUS SOIL</td><td></td><td colspan="6">CORN</td><td colspan="9"></td></tr>
<tr><td></td><td colspan="6">COWPEA</td><td colspan="9"></td></tr>
<tr><td></td><td colspan="6">CASSAVA</td><td colspan="9"></td></tr>
<tr><td rowspan="13">VOVOKAME</td><td>DEVELOPED LOWLAND</td><td></td><td colspan="7">RICE</td><td colspan="4">SWEET CORN</td><td colspan="4"></td></tr>
<tr><td rowspan="5">NON DEVELOPED LOWLAND</td><td colspan="8" rowspan="5">INTERCROP OR RICE</td><td colspan="4">EGGPLANT</td><td colspan="4"></td></tr>
<tr><td colspan="5">HOT PEPPER (long fruit)</td><td colspan="3"></td></tr>
<tr><td colspan="5">CABBAGE</td><td colspan="3"></td></tr>
<tr><td colspan="4">TOMATO</td><td colspan="4"></td></tr>
<tr><td colspan="8"></td></tr>
<tr><td rowspan="4">VERTISOL</td><td></td><td colspan="6">CORN</td><td colspan="3"></td><td colspan="4" rowspan="4">CORN</td><td colspan="2"></td></tr>
<tr><td></td><td colspan="6">HOT PEPPER (long fruit)</td><td colspan="3"></td><td colspan="2"></td></tr>
<tr><td colspan="3"></td><td colspan="4">TOMATO</td><td colspan="3"></td><td colspan="2"></td></tr>
<tr><td></td><td colspan="6">RICE</td><td colspan="3"></td><td colspan="2"></td></tr>
<tr><td rowspan="3">FERRUGINOUS SOIL</td><td></td><td colspan="6">CORN</td><td colspan="9"></td></tr>
<tr><td></td><td colspan="6">COWPEA</td><td colspan="9"></td></tr>
<tr><td></td><td colspan="6">CASSAVA</td><td colspan="9"></td></tr>
</table>

VILLAGES	AGROECOLOGICAL ZONES	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
HOUINGA	NON DEVELOPED LOWLAND	RICE									FALLOW						
	NON DEVELOPED LOWLAND (PERIPHERAL)					EGGPLANT					INTERCROP OR CORN						
						CORCHORUS											
						TOMATO											
						HOT PEPPER (round fruit)											
	VERTISOL		CORN									CORN					
			HOT PEPPER (long fruit)														
			TOMATO														
			CORCHORUS														
	FERRUGINOUS SOIL		CORN														
			COWPEA														
			CASSAVA														

Figure 16. Cropping calendar per agroecological zone for the three villages of the Mono Couffo regions.

3.5.1.4.1. Developed lowland

Virtually all farmers member of farmers' group have plots in this area in the villages of Agbedranfo and Vovokame. Periods of land development and cropping cover throughout the year due to the availability of water coming from the artesian wells (Figure 17). The cultivated crops are: rice (rainy season) and vegetables (e.g. okra, hot pepper, tomato, sweet corn and jute mallow (jute mallow or crincrin (*Corchorus olitorius*)) (dry season).

Figure 17. Artesian well at Agbedranfo (Benin).

At Vovokame during dry season, sweet corn was cultivated instead of vegetables, because parts of the plots were too wet for vegetables.

3.5.1.4.2. Non developed lowland

Near three quarters of farmers have plots in this agroecological zone. The difficulties of water supply due to the lack of land development limit the full time use of the plots. Cropping seasons are highly dependent on the rainfall.

At Agbedranfo, land development is intense during the period from December to May. These include the period of water recession where water retreats but remains available. Supplemental irrigations of crops are done with pumps or manually. Later most farmers abandon the plots (intercropping) or install corn, cassava on non-flooded plots. Recently, farmers have started cultivating rice in this area.

At Houinga, where developed lands are not functional, farmers cultivate rice in this zone at the onset of the rainy season. Hence rice is cultivated during the period of flooding from May to January by all farmers with staggered seeding/transplanting dates. After the rainy season, water recedes and the plots are almost all abandoned during the dry period. Some farmers drill small wells in their plots to collect water. Others install vegetable crops (at a very small scale) in the vicinity of the borehole. Unfortunately when the holes and the wells dry up, and fetching water from homes to irrigate the plots becomes very tedious, plots are definitively abandoned during the months of January and February.

A Vovokame, very few farmers have plots on the undeveloped parts of the lowlands. As at Houinga, some farmers take advantage of the flood to cultivate rice from May-June to September. These plots are abandoned after the harvest of rice. Others get supplemental irrigation from the artesian well. In this case, the proximity of plots with the artesian well allows cropping activities.

Cultivated crops in this non developed lowland vary to a lesser extent between the villages. At Agbedranfo, crops are okra, hot pepper and crincrin. In addition to these crops, tomato and eggplant are also grown in the other two villages (Houinga and Vovokame). Cabbage is only cultivated at Vovokame.

3.5.1.4.3. Vertisols

More than three quarters of farmers also cultivate on vertisols. This proportion varies between the villages: Agbedranfo and Vovokame have more farmers than Houinga. The land tenure issues may explain this situation. At Agbedranfo and Houinga, the land ownership is individual, while at Vovokame, the ownership is collective.

Rainfed cropping system is prevalent on vertisols in the three villages. The specificity of this area is the earliness of crops cultivations as early as March because of the fertility and water holding capacity of the vertisols. In a cropping year, two cycles of crops are conducted. Corn is cultivated first during the long rainy season. During the short rainy season, vegetable crops are cultivated in relay with corn. Vegetable crops include pepper (long fruit), okra, tomato, and on smaller areas crincrin and eggplant are cultivated. Other farmers proceed with a second cycle of corn. However at Vovokame, some producers have started experimenting rice cultivation during the flooding period of the zone.

3.5.1.4.4. Ferruginous soil

On ferruginous soils, farmers cultivate crops (cowpea, cassava, corn...) during the main rainy season (June to November). The cropping system is rainfed as on vertisols. Houinga has more farmers than Agbedranfo and Vovokame cultivating this area.

3.5.1.5. Location of the fields

3.5.1.5.1. Fields in 2010

Each site is composed of mosaic of fields occupied generally by mono crops (rice, vegetables), and palm trees, corn, and fallow fields. During the year, rotations are practiced at Agbedranfo and Vovokame, while at Houinga rice fields are generally fallowed. At Agbedranfo and Vovokame, during the same year 2010, rice fields cultivated during the rainy season were larger than the fields previously cultivated with vegetables (jute mallow and okra) and maize during the dry season.

3.5.1.5.2. Fields from year 2010 to year 2011

In general, the areas of the fields increased slightly from 2010 to 2011, by increments of areas resulting from the addition of areas destined to rice cultivation. That observation was obvious at Houinga, where there was a general tendency of increase of cultivated areas from 2010 following a temporal trend, with clearing of new fallow land for rice cultivation in 2011 (Figure 18).

2010 2011

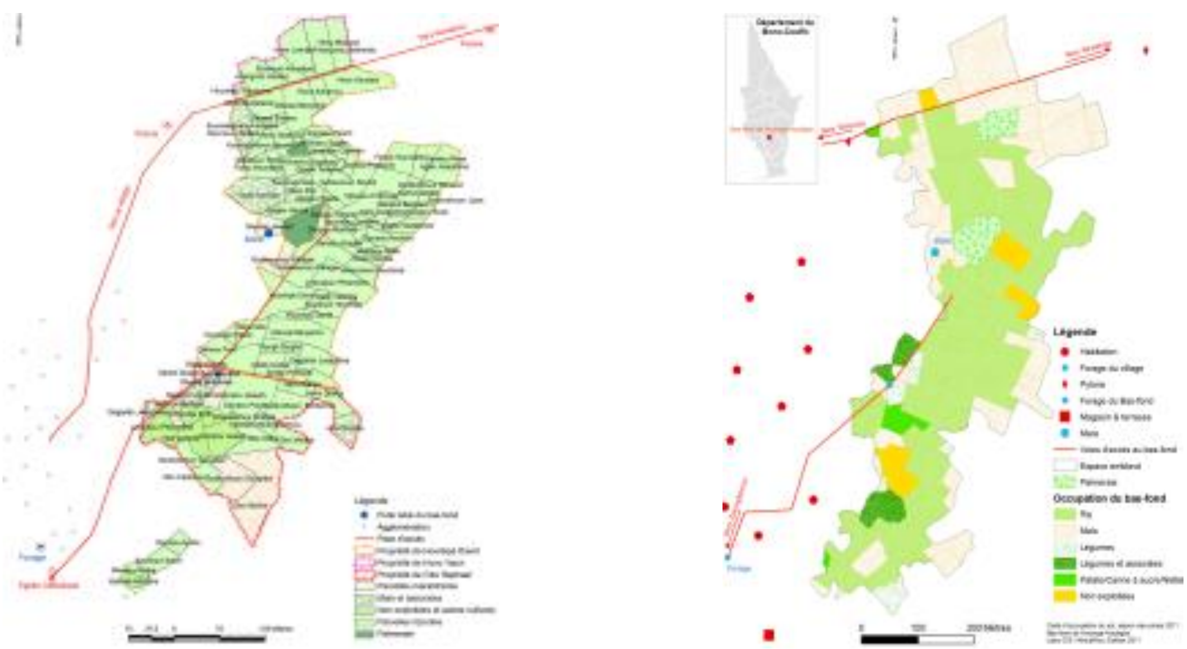


Figure 18. Fields location at Houinga during the rainy seasons 2010 and 2011.

At Houinga, in 2010, fields were initially installed in the wetter areas in proximity of the borehole, but in 2011, some farmers started clearing new fields situated on relatively higher toposequence positions like the hydromorphic fringes, and away from the borehole (Figure 18).

For the three sites, inside each individual field, the boundaries of the cultivated areas change from year to year. In this case, many individual fields were determined, with each of them representing a rather uniform surface where rice and/or vegetables are cultivated.

Each year, farmers burn the totality of the cleared fields towards the end of the dry season, and this burning destroy part of the weed seed bank present in the soil, resulting in dynamic vegetation. The main determinant is the frequency and severity of disturbances (clearing, burning...), and this time a strong relation is established between agricultural practices and field weed growth, although the soil proves to be important too. From year to year, weeds in fields can best be studied by means of repeated observations in permanent quadrats.

3.5.2. The Cote d'Ivoire key site

3.5.2.1. Location and characteristics of the study areas

The Pounjou key site is located east of Boundiali in north-west Cote d'Ivoire (Figure 19), where the dominant lithology is schist. The coordinates are 6.3 West Longitude and 9.5 N Latitude, and altitude at 370 m above sea level.

Figure 19. Map of North-West Cote d’Ivoire and location of the Pounjou key site.

3.5.2.2. Climate

The key site is situated in the Guinea Savanna agroecological zone which is characterized by a growing period of 165 to 270 days (Windmeijer and Andriesse, 1993). The growing period is defined as a continuous period during the year in which the average precipitation exceeds half the potential evapotranspiration, plus the number of days required to evaporate an assumed 100 mm of water stored in the soil (Windmeijer and Andriesse, 1993). The site has a monomodal rainfall regime with a humid period from June through September. Mean monthly rainfall and mean monthly temperature data are shown in Figure 20.

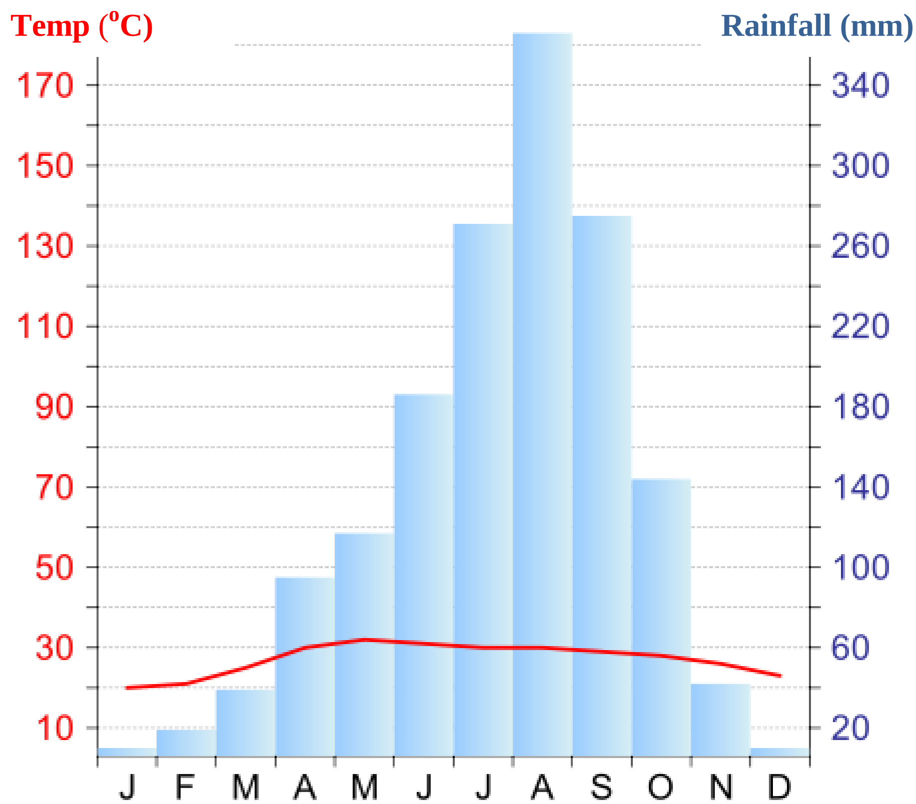


Figure 20. Mean monthly rainfall and mean monthly temperature in Pounjou (Source: AfricaRice).

3.5.2.3. Geology and landscape

Metamorphic rocks, mainly schists form the parent material of the geological formation of the study area. The formation is part of the basement complex of Precambrian age and the landscape is dominated by plateaux. The altitude varies between 350 and 450 m above sea level. Relief intensity, which is defined as the average difference between the top and bottom of the catena, is approximately 25 to 30 m (Beaudou and Sayol, 1980).

3.5.2.4. Vegetation

The woodland savanna covering the study area is mainly characterized by trees (*Isoberlinia dalzielii* and *Monotes kerstingii*). Common grasses are *Brachiaria* spp. and *Hyparrhenia* spp. on drier parts of the catena, and *Oryza longistaminata* in valley bottoms.

3.5.2.5. Farming systems

Framing systems were primarily determined by the main ethnic groups (Senoufo and Malinke) that live in the key area and the associated different land tenure systems (Windmeijer and Andriesse, 1993). The farming systems also varied with the location on the catena. Major food crops were maize, yam, rice, sorghum and millet. Cotton is the main cash crop, but rice, yam and vegetables are important commodities locally (Becker and Diallo, 1992). Generally, rice is the only crop cultivated in the valley bottom and on the hydromorphic fringes. On the crests, rice, cotton, maize, yam and vegetables are cultivated (Windmeijer and Andriesse, 1993).

3.6. Thesis outline

Chapter 1 covers the general introduction with the research question, hypotheses and the objectives of the thesis

Chapter 2 deals with the literature review highlighting the morphology of inland valleys, the evolution of lowland rice-based systems in West Africa, in physical, socio-economic and historical contexts. It describes the inland valley uses, the lingering land tenure cases and the management of abiotic and biotic factors

Chapter 3 exposes the context, approach, concepts and the general methodology of the studies

Chapter 4 addresses the core studies conducted in Benin. Weeds and farmers' weed management practices and perceptions along the catena in the Mono Couffo regions of Benin are discussed

Chapter 5 describes the response of lowland rice to agronomic management under different hydrological regimes along the catena in an inland valley. Results have been evaluated in terms of confirmation or contradiction of the recent results obtained in Benin with this *ex-ante* experimentation.

In Chapter 6, the overall results have been summarized and discussed in a broader context. Recommendations and potential bottlenecks for developing integrated agronomic management methods have been presented as outlook.

Chapter 4

Weeds and farmers' weed management practices and perceptions along the catena in the Mono Couffo regions of Benin

4.1. Weed communities of rice based production systems along the inland valley catena in the Mono Couffo regions of Benin

4.1.1. Introduction

Inland valleys are largely unexploited land resources with an estimated total surface area of 85 million ha in West Africa (Windmeijer and Andriesse, 1993). These agro-ecosystems are characterized by more fertile, heavy textured soil and a generally favorable hydrological regime (Andriesse et al., 1994; van der Heyden and New, 2003). Inland valleys are therefore areas with a high potential for the development of rice-based production systems (Rodenburg et al., 2013).

Intensification and diversification practices are frequently observed in inland valleys in West Africa (Erenstein et al., 2006b). Rice and vegetables are the first and second most important food crops produced in these ecosystems. These crops are either grown in rotations or as sole crop, with rice during the wet season (in West Africa: May to November) and vegetables growing on residual soil moisture in the dry season (West Africa: December to April).

Most inland valleys have an undulating topography and high spatial variability in soil and hydrology (Windmeijer et al., 2002). Due to sediment deposition in the valley bottom, inland valleys are often characterized by a gradient of soil texture, and related physical and chemical properties, with coarser soil texture on the valley crests or crest and increasing finer textures going downslope. Seasonal flooding is most likely to occur in the valley bottom while drought is common on the fringe. Hence, apart from a soil fertility and texture gradient there is a hydrological gradient along the catena (Ogban and Babalola, 2009). Such environmental conditions together with the management practices will determine weed species occurrence along the catena. Weeds are particularly problematic in rice fields where water cannot be controlled (Rodenburg et al., 2009). It is for this reason that in West African inland valley rice production systems, that often lack effective water control and in field-grown tomatoes production systems, weeds constitute one of the main factors limiting crop production (Becker et al., 2003; Huat et al., 2013).

It is hypothesized that submergence environmental conditions and cropping systems based on rotations of crops with different planting dates and growth periods, contrasting competitive characteristics, and dissimilar management practices may reduce the build-up of populations of dominant and competitive weed species (Rao et al., 2007; Rodenburg and Johnson, 2009). Understanding the implications of different environmental conditions and inland valley rice-based cropping systems for the weed flora will be instrumental for the development and fine-tuning of weed management recommendations. Such recommendations would contribute to back-stopping farmers in rice-based systems with the ultimate aim to promote rice-based production systems in inland valleys as a crop intensification and diversification strategy to fulfill the inland valleys potential to contribute to food security and poverty alleviation. The objectives of this study were to assess the weed community composition of rice-based systems in inland valleys, to identify the dominant weed species and to understand if, how and why species' dominance is related to environmental factors and management practices along the catena.

4.1.2. Materials and methods

4.1.2.1. Study sites

The study was conducted during the 2010 and 2011 cropping seasons in three inland valleys, near the villages Agbedranfo, Vovokame and Houinga, in the departments of Mono (1,860 km^2) and Couffo (2,250 km^2) in south-western Benin. The study sites, located in southern Guinea Savanna zone of West Africa, are characterized by a bi-modal rainfall regime. These sites were representative for lowland rice (*Oryza sativa*) based production systems in West Africa and were selected based on contrasting agricultural potential for rice production and crop diversification (Windmeijer and Andriesse, 1993). At Agbedranfo and Vovokame rice production was supported by well-functioning irrigation infrastructure (artesian wells). At Agbedranfo, crop rotation was practiced, with rice during the rainy season, along the whole catena, and vegetables mainly during the dry season. Jute mallow (*Corchorus olitorius*) was cultivated mainly at positions in the hydromorphic fringe and valley bottom, while okra (*Abelmoschus esculentus*) was cultivated on the drier fringes of the catena. At Vovokame, rice was rotated with maize (*Zea mays*), with rice during the rainy season, and maize during the dry season. At Houinga valley rice production was rainfed, because the irrigation infrastructure was not functional. Hence rice was cultivated during the period of flooding from May to January along the catena. After the rainy season, water receded and the plots were almost all abandoned during the dry period. A detailed physical characterization of the study sites is presented in Table 3.

Table 3. Characterization of the study sites.

		Agbedranfo	Vovokame	Houinga
Geography and environment	Department	Mono	Mono	Couffo
	Municipality	Dogbo	Dogbo	Houeyogbé
	Coordinates	1°72' E 6°76' N	1°75' E 6°79' N	1°82' E 6°59' N
	Growing period (days)	225	225	240
	Mean annual rainfall (mm)	950	950	1100
	Lowland area (ha)	40	12	200
Agronomy	Tillage	Manual/tractor	Manual	Minimum manual tillage
	Seeding methods for rice	Dibbling in lines	Dibbling in lines	Transplanting
	Rice varieties	Improved	Improved	Improved and traditional
	Vegetable varieties	Traditional	-	-
	Intercrops	Okra and hot pepper	-	-
	Rotation crops	Rice/vegetable	Rice/maize	-
	Fertilizer use	NPK and urea	NPK and urea	NPK and urea
	Irrigation	Artesian well	Artesian well	None
	Weed control	Manual	Manual	Manual and herbicide

4.1.2.2. Field observations

From 2010 to 2011, observations were conducted in 45 different farmers' fields with rice, jute mallow, okra or maize as main crops, divided over 3 inland valleys. In 2010, observations were conducted in 41 fields, and repeated at the same sites which were incremented with 4 fields in 2011, giving a total of 86 plots surveyed during the two years (Table 4).

Table 4. Number of plots surveyed per cropping season and per cropping systems.

Cropping season	Village	Cropping systems				Total
		Rice-Jute mallow	Rice-okra	Rice-maize	Rice-fallow	
2010	Agbedranfo	15	3	-	-	18
	Vovokame	-	-	12		12
	Houinga	-	-	-	11	11
2011	Agbedranfo	14	4	-		18
	Vovokame	-	-	13		13
	Houinga	-	-	-	14	14
Total		29	7	25	25	86

For the characterization of the weed flora and land use, four to six transects were randomly laid out through cropped fields in each of the valleys. These transects were oriented along the main direction of the valley stream, hence from upland to lowland, to capture the whole range of physical and biotic conditions along the catena. The parallel transects were all 80-100 m long and 80-100 m apart from each other. In each farmer's field along these transects weeds were sampled using two randomly placed quadrats of 6 m^2. The size of each farmer's field was between 400 and 2400 m^2, and each field represented one repetition with averaged value of the two quadrats. On average there were five to seven sampling fields along each transect, separated by 15-20 m. Observations on the weed flora were done before crop establishment (pre-season), and at 28, 56 and 84 days after seeding (DAS) and at harvest for rice and maize. For vegetable crops, observations were done at pre-season, and at 15, 30, 45, 60 and 75 DAS. Vegetation sampling points in the quadrats were spatially referenced with GPS coordinates and their position on the catena was noted using three broad categories: 1) inland valley crest, 2) hydromorphic fringe and 3) valley bottom. Percentage soil coverage (the ground area covered by the vertical projection of above-ground plant parts) was estimated visually for each of the weed species in each quadrat and scored on a scale from 0 to 9 (0: absence; 1: 1%; 2: 7%; 3: 15%; 4: 30%; 5: 50%; 6: 70%; 7: 85%; 8: 93%; 9: 100%) (Marnotte et al., 2004). These weed species percentage soil coverage scores were used to calculate the local coverage (Cl) and the corrected mean coverage (Cmc) of weed species as:

Local coverage (Cl) = $\sum$ coverage / n Equation 2

Where $\sum$ coverage represents the sum of weed coverage scores for the concerned species in all samples and n represents the number of samplings points where the specie is present. From this, the corrected mean coverage (Cmc) was calculated as:

Corrected mean weed coverage (Cmc) = Cl/CL Equation 3

Where Cl represents the local coverage of a species with an ecological (or environmental) class (e.g. clayey or sandy soil) of a special factor such as soil and CL means the local coverage of a species for all classes (e.g. all soils) combined. The local coverage reveals species with less frequent presence but with high coverage rates where present. The corrected mean coverage is equivalent to 'corrected profile' or 'ecological profile' and is used to link the presence of a species to a special factor, such as catena position, or soil class, etc. Values of Cmc close to 1 indicate that the species is not closely linked (hence independent) to the ecological class (Marnotte et al., 2004).

For each weed species, the relative frequency was also assessed, as:

Relative frequency (Fr) = 100*n/N Equation 4

Where, n represents the number of sampling points where the species is present, and N represents the total number of sampling points. Hence the relative frequency of a species is expressed as the percentage of plots in which the species was present.

Weeds were identified and described at the genus and species level according to illustrated handbooks of Akobundu and Agyakwa (1987), Johnson (1997)and a tool for computer aided identification (IDAO) for weeds of rice in Africa (Grard et al., 2013). Unidentified weeds in the field were tagged, pressed and identified in the herbarium of the University of Abomey-Calavi.

Biological life form is characterized by the adaptation of plants to certain ecological conditions such as the dry season in tropical areas which implies the cessation or slowing of vegetative growth (Galán et al., 1999). In this study, a simplified weed species classification based on Raunkiær's classification (Galán et al., 1999) was used with five life forms: 1) Geophytes (G), being perennial herbaceous plants with growing buds below the ground surface - plants with bulbs, rhizomes or tubers, 2) Helophytes (Hl), being perennial plants rooted under water with reproductive organs above the water surface, 3) Hemicryptophytes (Hm), being perennial herbaceous plants with growing buds above the ground surface, with a well-developed root system - predominating in various types of grassland, 4) Phanerophytes (P), being woody plants with growing buds more than 50 cm above the surface - trees, shrubs and lianas and 5) Therophytes (T), being annual plants which survive adverse season through their seeds. Species were also classified according to their photosynthetic pathways (C_3 or C_4) based on data compiled by various authors (Akobundu, 1987; Ehleringer et al., 1997; Elmore and Paul, 1983).

Two soil cores to a depth of 20 cm were taken from each quadrat and bulked with the two cores of the second quadrat from the same field to form a composite soil sample for each field. Soil samples were analyzed for particle distribution and chemical properties (organic C, N total, available P (Mehlich), and pH water) at the AfricaRice Analytical Services Laboratory, Cotonou, Benin.

Data on crop management (cropping systems, fertilizer and herbicide uses) were collected in each field through farmer interviews and direct observations in the fields.

4.1.2.3. Data analyses

Levels of qualitative variables such as environmental and crop management variables (village location, cropping systems, fertilizer and herbicide uses) were converted into binary dummy variables. Soil data were considered as quantitative variables.

As relative frequency and corrected mean coverage are not normally distributed, they were subjected to an ANOVA using the Generalized Linear Model approach (McCullagh and Nelder, 1989). The R statistical software was used (R Core, 2013) for the computing.

A detrented correspondence analysis (DCA) was performed on weed species' relative frequency data to determine that unimodal analyses were appropriate with gradient lengths over 3.0 standard deviations. Then, the data were subjected to Canonical Correspondence Analysis (CCA) where effects of environmental variables (village location, cropping systems, soil chemical properties, texture) and management factors (e.g. fertilizer and herbicide use) on weed species composition was tested using methods recommended by Ter Braak and Smilauer (1998), establishing major factors influencing plant community composition. The unrestricted Monte-Carlo test was used to test the importance of the ordination on the first and second axis at the 5% level of probability. The CANOCO 4.0 computer software was used for data analyses (Ter Braak and Smilauer, 1998) and default options were used. Species with relative frequency <5% were left out from the analyses.

4.1.3. Results

4.1.3.1. Weed flora analysis

In a total of 45 rice and vegetables fields, weeds from 28 different families were observed, with a total of 95 fully- identified species (75 in 2010 and 84 in 2011) (Appendix A). More than 64% of the weed flora was composed of Dicotyledons species. Important Dicotyledon families were the *Asteraceae* (12% of all species), *Euphorbiaceae* (7%), and *Amaranthaceae* (5%) (Appendix A). The remaining 42% are divided over 23 families, illustrating the highly diverse nature of weed communities in these rain-fed lowlands.

Four groups of weeds species were distinguished based on relative frequency (*Fr*) and local coverage (*Cl*) (Figure 21). Group 1 (*Fr*>30% and *Cl*>10%) constituted the most dominant species i.e. *Ageratum conyzoides*, *Digitaria horizontalis*, *Paspalum scrobiculatum* and *Synedrella nodiflora*. Group 2 (20% ≤ *Fr* ≤ 30% and 10% ≤ *Cl* ≤ 20%) featured relatively frequently observed species with moderate coverage, i.e. *Basilicum polystachyon*, *Echinochloa colona*, *Ludwigia decurrens*, *Panicum laxum* and *Physalis angulata*. Group 3 (*F*r<10% and *Cl*>10%) included less frequent species with relatively high coverage i.e. *Bacopa decumbens*, *Commelina benghalensis*, *Dactyloctenium aegyptium*, *Euphorbia heterophylla*, *Fimbristylis ferruginea*, *F. littoralis*, *Heteranthera callifolia*, *Imperata cylindrica* and *Leersia hexandra* and Group 4 (*F*r≤20% and *Cl*<10%) comprised minor species i.e. *Alternanthera sessilis, Amaranthus spinosus*, *Corchorus aestuans*, *Eclipta prostrata*, *Ipomoea aquatica* and *Talinum triangulare*.

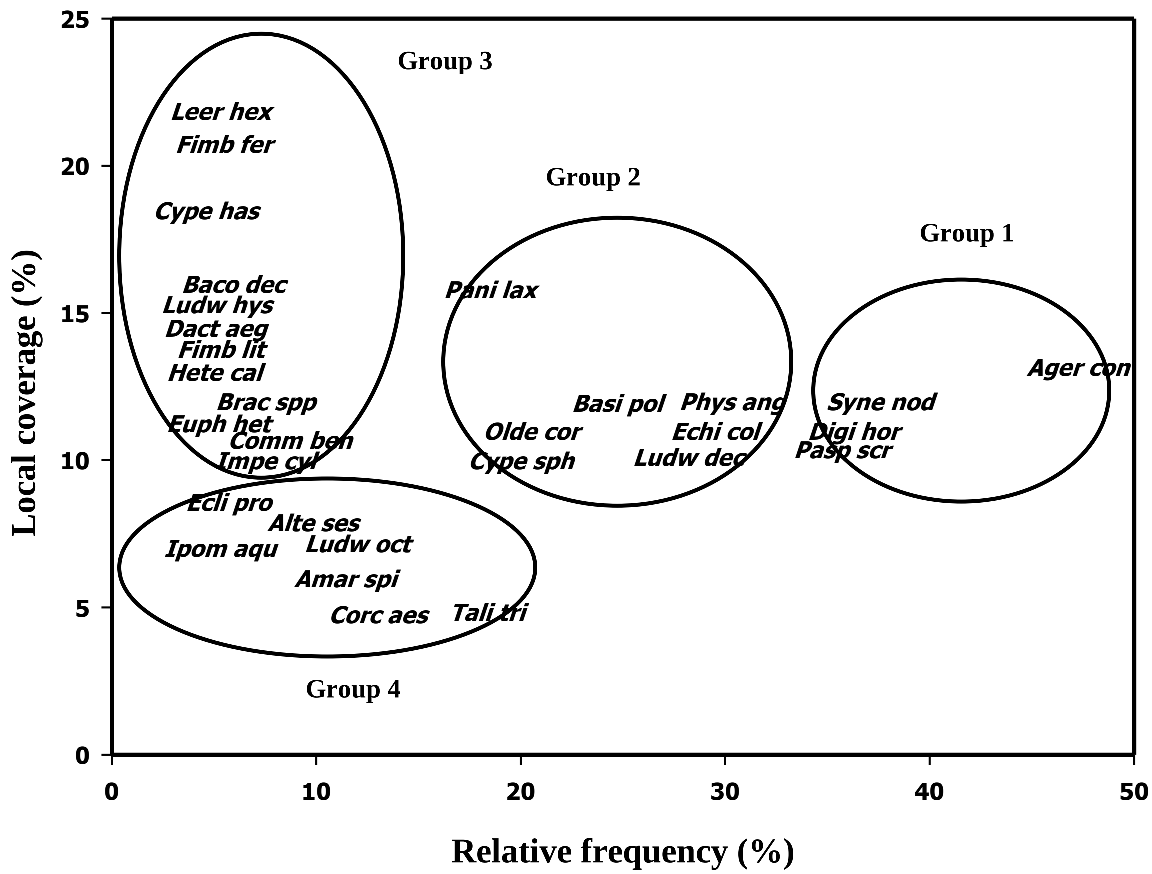


Figure 21. Relationship between major weed species relative frequency and local coverage for the three sites in 2010 and 2011. Keys to species names are given in Appendix A.

Group 1 (Fr>30% and Cl>8%) constituted the most dominant species i.e. *Ageratum conyzoides*, *Digitaria horizontalis*, *Paspalum scrobiculatum* and *Synedrella nodiflora*. Group 2 (20% ≤ Fr ≤ 30% and 8% ≤ Cl ≤ 20%) featured relatively frequent and covering species i.e. *Basilicum polystachyon*, *Echinochloa colona*, *Ludwigia decurrens*, *Panicum laxum* and *Physalis angulata*. Group 3 (Fr<10% and Cl>8%) included less frequent species with high coverage i.e. *Bacopa decumbens*, *Commelina benghalensis*, *Dactyloctenium aegyptium*, *Euphorbia heterophylla*, *Fimbristylis ferruginea*, *Fimbristylis littoralis*, *Heteranthera callifolia*, *Imperata cylindrica* and *Leersia hexandra* and Group 4 (Fr≤20% and Cl<10%) comprised minor species i.e. *Alternanthera sessilis*, *Amaranthus spinosus*, *Corchorus aestuans*, *Eclipta prostrata*, *Ipomoea aquatica* and *Talinum triangulare*.

4.1.3.2. Weed species' biology and physiology

Therophytes constituted 76% of the species surveyed in the three lowlands. Perennials comprised geophytes (11%), hemicryptophytes (6%), helophytes (4%) and phanerophytes (3%) (Appendix A).

From 44% of the weed genera observed in this study the photosynthetic pathway was not known. Of the remaining 56%, 62% of the weed genera use the C_4 pathway, while 38% use the C_3 pathway (Appendix A). Of the 33 C_4 species, 23 were Monocotyledoneae, of the *Graminaea* (17 out of 18 species with known pathways) and the *Cyperacea*e (six out of eight species with known pathways) family. The other C_4 species were of the *Amaranthaceae* (4 species), *Euphorbiaceae* (3 species), *Portulacaceae* (2 species), and *Nyctaginaceae* (1 species) family. The 20 C_3 species included the family of *Asteraceae* (8), *Commelinaceae* (3); all species of this genera), *Capparidaceae*, *Convolvulaceae*, and *Cyperaceae* (2), and *Amaranthaceae, Graminaea* and *Papilionaceae* (1). According to corrected mean coverage (*Cmc*), C_4 species such as *D.*

aegyptium (*Cmc* = 3.02), *D. horizontalis* (1.81) and *A. spinosus* (1.60) were mainly found on the valley crest position, whereas C_3 species comprising *I. aquatica* (2.68) and *E. prostrata* (1.46) were found in the valley bottom position (Table 5).

Table 5. Relative frequency (Fr) and corrected mean coverage (Cmc) of weeds species differentiated at catena positions during the two years of study at the three sites.

Species	Catena position[a]					
	VC	HF	VB	VC	HF	VB
	Fr (%)			Cmc		
Amaranthus spinosus	8	5	3	1.60	0.88	0.53
Brachiaria spp.	10	8	4	1.95	0.62	0.45
Commelina benghalensis	25	5	6	2.18	0.42	0.41
Corchorus aestuans	10	15	2	1.04	1.95	0.07
Cyperus sphacelatus	4	11	14	0.34	1.05	1.59
Dactyloctenium aegyptium	3	0	0	3.02	0.00	0.00
Digitaria horizontalis	52	29	28	1.81	0.60	0.60
Eclipta prostrata	5	10	8	0.51	1.01	1.46
Fimbristylis ferruginea	2	3	5	0.20	0.73	2.01
Heteranthera callifolia	0	2	3	0.34	0.87	1.76
Ipomoea aquatica	1	1	11	0.12	0.11	2.68
Leersia hexandra	0	0	7	0.00	0.00	2.90
Ludwigia hyssopifolia	1	2	1	0.48	2.11	0.46
Ludwigia octovalvis	7	16	8	0.53	1.72	0.77
Panicum laxum	5	29	21	0.11	1.28	1.59
Test[b]						
Mean	9	9	8	0.95	0.89	1.15
P-value		<0.0001			0.9999	

[a] VC = valley crest; HF = hydromorphic fringe; VB = valley bottom.

[b] One-way ANOVA using Generalized Linear Model for relative frequency and corrected mean coverage.

4.1.3.3. Weeds species' ecology

Table 5 shows the species distribution along the inland valley catena. Weeds thriving on the inland valley crests were: *D. aegyptium* (3.02), *C. benghalensis* (2.18), *Brachiaria* spp. (1.95), *D.*

horizontalis (1.81) and *A. spinosus* (1.60). Weeds of the (sloping) hydromorphic zones, based on the corrected mean coverage values, were: *Ludwigia hyssopifolia* (2.11), *C. aestuans* (1.95) and *Ludwigia octovalvis* (1.72). In the valley bottom, following weeds, based on corrected mean coverage values were: *L. hexandra* (2.90), *Ipomoea aquatica* (2.68), *F. ferruginea* (2.01), *H. callifolia* (1.76), *Cyperus sphacelatus* (1.59), *P. laxum* (1.59) and *Eclipta prostrata* (1.46).

I. aquatica (Cmc: 2.71), *F. littoralis* (2.68), *L. hexandra* (2.67), *F. ferruginea* (2.47), *E. colona* (1.82) and *C. sphacelatus* (1.53) were common in rice - jute mallow systems, mostly cultivated in the valley bottoms and hydromorphic fringes (Table 4). In rice - okra system mainly found on the drier valley crests, *C. benghalensis* (5.13), *D. horizontalis* (2.98), *E. heterophylla* (2.93) and *A. spinosus* (2.50) were most common. In rice - maize systems, encountered in the valley bottom and hydromorphic fringes, *L. hyssopifolia* (3.50), *P. laxum* (3.39), *C. aestuans* (3.04) and *E. prostrata* (2.58) were common. For rice - fallow systems covering the whole upland-lowland continuum, from the valley bottom to the valley crests, *B. decumbens* (3.91), *H. callifolia* (3.91), *I. cylindrica* (3.42) and *B. polystachyon* (3.05) were most common.

The dominant weeds growing during the dry seasons in vegetables were more or less dryland upland weeds such as *Echinochloa colona* (Cmc: 4.27), *Cleome viscosa* (4.07), *T. triangulare* (4.05), *Spigelia anthelmia* (3.44), *Brachiaria* spp. (2.89), *Portulaca oleracea* (2.84), *Amaranthus viridis* (2.66), *C. benghalensis* (2.38), *T. procumbens* (2.36), and *Cyperus rotundus* (2.28) (Table 5). During the rainy seasons, aquatic and semi-aquatic weeds growing in lowland rice included weeds such as *L. hexandra* (Cmc: 3.69), *L. octovalvis* (3.39), *I. aquatica* (2.48), *Sphenoclea zeylanica* (2.31), and *Fimbristylis ferruginea* (1.84).

For the overall weed species ecological growing conditions comprising the position on the catena, the cropping systems and the growing seasons across the three sites, the corrected mean coverage did not show significant differences for the distribution of the different major weed species whereas for the relative frequency, there were highly significant differences between weed species (Tables 5, 6 and 7). Frequent species (e.g. *A. conyzoides* and *S. nodiflora*) with Cmc close to 1 were independent to the different ecological classes and did not feature in Tables 3, 4 and 5.

Table 6. Relative frequency (Fr) and corrected mean coverage (Cmc) of weed species differentiated by cropping systems during the two years of study at the three sites.

Species	Cropping systems [a]							
	JM/R	O/R	M/R	F/R	JM/R	O/R	M/R	F/R
	Fr (%)				Cmc			
Amaranthus spinosus	6	12	0	0	0.72	2.50	0.00	0.00
Bacopa decumbens	0	0	0	23	0.00	0.00	0.00	3.91
Basilicum polystachyon	4	1	21	68	0.12	0.00	0.66	3.05
Commelina benghalensis	15	54	2	0	1.00	5.13	0.21	0.00
Corchorus aestuans	2	8	25	3	0.07	0.72	3.04	0.35
Cyperus sphacelatus	13	1	16	3	1.53	0.02	1.44	0.21
Digitaria horizontalis	41	74	25	25	0.88	2.98	0.69	0.63
Echinochloa colona	44	37	25	10	1.82	1.08	0.58	0.22
Eclipta prostrata	2	0	18	8	0.18	0.00	2.58	0.98
Euphorbia heterophylla	16	33	7	0	1.27	2.93	0.77	0.00
Fimbristylis ferruginea	7	0	1	2	2.47	0.00	0.16	0.19
Fimbristylis littoralis	9	0	1	1	2.68	0.00	0.05	0.01
Heteranthera callifolia	0	0	0	6	0.00	0.00	0.00	3.91
Imperata cylindrica	1	4	1	15	0.08	0.63	0.09	3.42
Ipomoea aquatica	13	1	0	0	2.71	0.04	0.00	0.00
Leersia hexandra	6	0	1	0	2.67	0.00	0.08	0.00
Ludwigia hyssopifolia	0.5	0	5	0	0.20	0.00	3.50	0.00
Panicum laxum	2	0	57	11	0.08	0.00	3.39	0.29
Test[b]								
Mean	10	13	11	10	1.03	0.89	0.96	0.95
P-value		<0.0001				0.9997		

[a] JM/R = jute mallow/rice; O/R = okra/rice; M/R = maize/rice; F/R = fallow/rice.

[b] One-way ANOVA using Generalized Linear Model for relative frequency and corrected mean coverage

Table 7. Relative frequency (Fr) and corrected mean coverage (Cmc) of weed species differentiated by cropping season during the two years of study at the three sites.

Species	Dry season	Rainy season	Dry season	Rainy season
	Fr (%)		Cmc	
Amaranthus viridis	6	1	2.66	0.49
Brachiaria spp.	13	6	2.89	0.44
Cleome viscosa	16	0	4.07	0.06
Commelina benghalensis	22	10	2.38	0.88
Cyperus rotundus	13	2	2.28	0.61
Echinochloa colona	27	0	4.27	0.00
Fimbristylis ferruginea	1	4	0.18	1.84
Ipomoea aquatica	3	13	0.88	2.48
Leersia hexandra	1	11	0.18	3.69
Ludwigia octovalvis	2	18	0.27	3.39
Portulaca oleracea	9	1	2.84	0.44
Sphenoclea zeylanica	0	8	0.00	2.31
Spigelia anthelmia	30	4	3.44	0.25
Talinum triangulare	4	0	4.05	0.07
Tridax procumbens	9	2	2.36	0.58
Test[a]				
Mean	10	5	2.18	1.17
P-value	<0.0001		0.9995	

[a] One-way ANOVA using Generalized Linear Model for relative frequency and corrected mean coverage.

Weeds were found in soils along the catena with texture ranging from sandy clay loam to clay loam and with moderate fertility (Table 8). In order to get an overview of the data structure and the importance of some chosen explanatory variables (soil and cropping management data), the data set for major weed species was submitted to canonical correspondence analysis.

Table 8. Selected properties of upper 20 cm of soil sampled in 2010-2011 along the catena in the surveyed fields.

Properties	Valley crests	Hydromorphic fringe	Valley bottom
Sand (%)	48	40	36
Clay (%)	32	34	38
Total N (g kg^{-1})	1.52	1.64	1.78
Total C (g kg^{-1})	16.60	17.40	19.50
Mehlich P (mg kg^{-1})	52.10	51.30	25.60

4.1.3.4. Canonical correspondence analyses

The first canonical axis, as well as all canonical axes, were highly significant ($P < 0.01$; F-ratio = 2.915 in both Monte Carlo Permutation tests; 199 permutations under the reduced model), indicating a strong relationship between the species and the environmental variables considered. Only the most frequent species are shown in Figure 22. Weed species composition was related to 15 environmental and management variables. The species and environment correlation with the first and second axis was 0.97 and 0.92 respectively. The first two ordinations explained 59.1% of the total variance with respect to relative frequency of the species as a function of the environment variables (Table 7). The first axis ($\lambda_1 = 0.313$) of the ordination diagram was most closely associated with soil texture as indicated by the high interset correlations of 0.882 and -0.815 for clay and sand content respectively, whereas the second axis ($\lambda_2 = 0.206$) could be explained by pH and available P influences (Table 6). *I. cylindrica*, *L. octovalvis* and *E. prostrata* occurred mainly in sandy soils. *A. spinosus*, *C. benghalensis* and *I. aquatica* were associated with high soil nitrogen content and with high clay content and high organic carbon.

Soil pH and available P closely associated with the rice-fallow system influenced mainly the frequency of *B. polystachyon*, *B. decumbens* and *Mariscus alternifolius*.

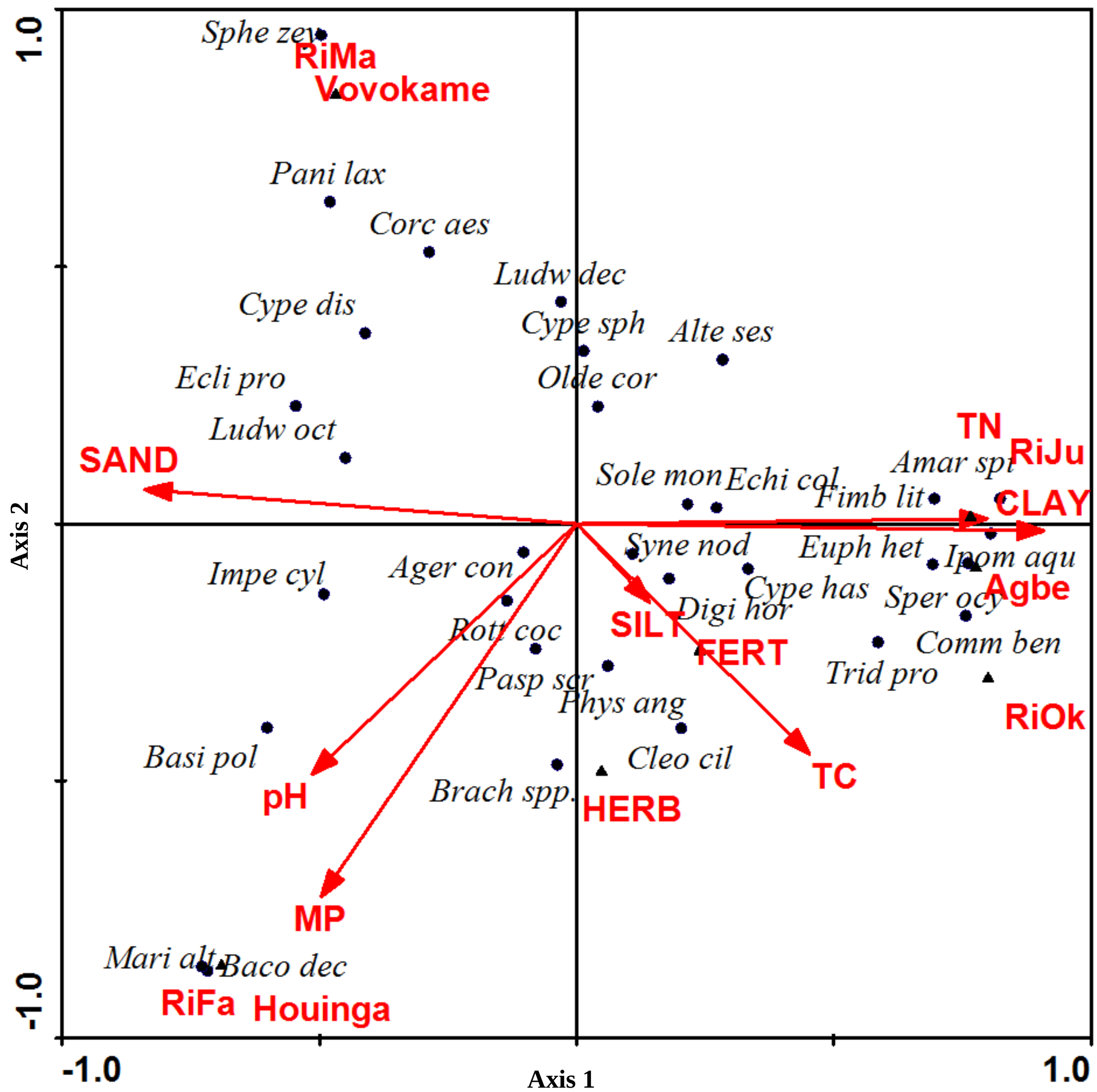


Figure 22. Ordination diagram of species and environmental and management variables of a CCA of weed cover data. Keys to the environmental and management variables and species names are given in Table 9 and Appendix A. The quantitative variables are represented by vectors, the nominal variables by upright rectangles and the species by circles. Only the most frequent species are indicated.

Table 9. Interset correlations of environmental and crop management variables with the first two ordination axes from a CCA of weed survey data.

Variable	Axis 1	Axis 2
Villages		
Agbedranfo (Agbedran)	0.955	-0.099
Houinga	-0.592	-0.697
Vovokame	-0.455	0.766
Inputs		
Fertlizer use (FERT)	0.451	-0.440
Herbicide use (HERB)	0.061	-0.566
Cropping systems		
Rice/fallow (RiFa)	-0.592	-0.697
Rice/jute mallow (RiJu)	0.706	0.010
Rice/maize (RiMa)	-0.455	0.766
Soil parameters		
Clay	0.882	-0.013
Sand	-0.815	0.061
Silt	0.138	-0.140
Carbon total (TC)	0.440	-0.411
Nitrogen total (TN)	0.775	0.001
Phosphorus Mehlich (MP)	-0.481	-0.666
pH(water)	-0.500	-0.447

Cropping systems were closely linked to positions on the catena and to the locations of the surveyed villages. Rice followed by dry season irrigated maize at Vovokame was associated with a higher occurrence of *Sphenoclea zeylanica* and *P. laxum*. Concerning the external inputs, only fertilizers use had a moderate effect on weed species frequency by being associated with the intensive cropping systems of rice-jute mallow and rice-okra. Herbicide use had its centroid near the origin with a low interset correlation (Table 9). Hence, herbicide use was less important in explaining the variation in weed species frequency. Frequent species, such as *A. conyzoides*, *S.*

nodiflora, *D. horizontalis*, *Solenostemon monostachyus*, *Rottboellia cochinchinensis*, *Paspalum polystachyum*, and *P. angulata* were located near the origin of the ordination diagram (Figure 21) indicating their ability to thrive under a diversity of ecologies.

4.1.4. Discussion

4.1.4.1. Weed community composition and biology life forms in inland valley rice-based systems

There were no clear relations between the biological life forms and the weed species presence along the catena. Apart from *P. scrobiculatum* the dominant weed species encountered in the inland valleys in this study were therophytes, annual species with short growth cycle (*A. conyzoides*, *S. nodiflora*, and *D. horizontalis*). Those weeds have a very plastic growth habit and are adapted to variable climatic conditions and cultural practices. They may emerge throughout the entire growing seasons and respond to fertilizers with hand hoeing weed control practices (Akintoye et al., 2011). Annual broad-leaved problem weeds in the inland valleys were *C. benghalensis* and *E. heterophylla*. *C. benghalensis* has a high vegetative propagation potential; it can propagate through cut segments following manual hoe weeding or cultivation. In turn, a single plant can cover a large area, and the species is somewhat resistant to herbicides (Le Bourgeois and Marnotte, 2002). *E. heterophylla* can rapidly form a closed canopy; it has a very short life cycle and can rapidly form a large population. Seeds are dispersed explosively through dehiscent seed capsules and germination can occur throughout the season due to the variable dormancy of the seeds (Rodenburg and Johnson, 2009). Although the number of species was quite low, some perennial weeds with geophyte life form (e.g. sedges like *F. ferruginea* and *Cyperus haspan*, and grasses such as *L. hexandra* and *I. cylindrica*) had a relatively high local coverage in the surveyed inland valleys. These species are potential problem weeds for farmers as they are able to multiply rapidly through tubers, bulbs, and seeds (sedges) or rhizomes and seeds (grasses) and they should therefore be given priority in weed management practices (Rao et al., 2007). The underground structures of these weeds can break into multiple smaller parts during mechanical weeding and those parts remain in the soil ready to resprout (Akobundu, 1987). Weed control measures in rice, vegetables and maize in the study areas are usually hand-hoeing and hand-pulling by farmers. As there is little use of herbicides, agrochemicals exert only a marginal selection pressure on the weed flora, allowing selective weeding operations. Thus some of the minor weeds such as *A. sessilis*, *E. prostrata*, *T. triangulare*, *C. aestuans*, *A. spinosus* and I. *aquatica* were purposely left in the field or removed before the actual weeding operations, as they were used for human consumption or medicinal uses, a practice that has been reported before (Rodenburg et al., 2012). For instance, the helophytic species *I. aquatica* is consumed by humans during the hunger gap period in some rural areas of West Africa (Akobundu, 1987), and *E. prostrata* was used by farmers as anti-venom against snakebite. (Achigan-Dako et al., 2011) reported *A. sessilis*, *T. triangulare* and *Corchorus* spp. as consumed wild vegetables in Benin.

4.1.4.2. Physiological reasons for species distribution along the catena

Global changes, like increasing concentrations of atmospheric greenhouse gases, temperatures, and rainfall irregularities will affect weed communities in Africa and management strategies must be adapted to take such effects into account (Fuhrer, 2003; Rodenburg et al., 2011). Plants have physiological and morphological characteristics that make them adapted to specific environmental conditions (Zhang et al., 2004). An important means of environmental adaptation of plants is through their photosynthetic pathways. There are three such pathways, referred to as C_3, C_4 and CAM, each with its own set of advantages and disadvantages. These differences in photosynthetic pathways result by and large in environmental differentiation. Prospected increased temperatures and limited soil moisture conditions (drought) may favor the growth of C_4 species over C_3 species, but elevated atmospheric CO_2 levels will have an opposite effect (Rodenburg et al., 2011). C_4-type weeds species are most observed in the free-draining upland rice growing environments, while C_3 species dominate the lowlands (Rodenburg et al., 2011). In the present study, the widespread occurrence of *Graminaea* with C_4 photosynthesis pathways could be an indication of the occurrence of temporary drought conditions in the surveyed inland valleys. There were differences in the distribution of weeds which were related to their photosynthetic pathways along the catena. C_4 was mostly found on valley crests with lower indices of available moisture. In contrast, valley bottom position consisted mainly of C_3 species. Edwards and Smith (2010) found that C_4 grasses were associated with reductions in mean annual precipitation, and found evidence that such species gradually moved from tropical forests into open, tropical savannas as their preferred niche. The transition zone between the valley crest and valley bottom (hydromorphic fringe) was rather very narrow with few sampling points, and did not have a distinct effect on the weeds distribution according to their photosynthesis pathways. More intensive quantitative sampling is needed to define the real pattern of weeds distribution according to their photosynthesis pathways along the catena of inland valleys.

4.1.4.3. Weed species distribution along the catena

The composition of a weed community in arable fields is a result of interactions effects between environment and past and current management practices (Tamado and Milberg, 2000). For rain-fed lowland rice, the duration of waterlogging and water depth, for instance, are among the factors affecting the weed species composition in a given field (Kent and Johnson, 2001). Indeed, weeds can be controlled by maintaining a continuous flood water layer (Becker and

Johnson, 1999a; Touré et al., 2009). Kent and Johnson (2001) reported that a shallow flooding of 2 cm is sufficient to reduce the emergence and growth of a number of weeds such as *F. littoralis* and *E. colona*. But some aquatic perennial species such as *I. aquatica* (with hollow floating stems) and *L. hexandra* are able to withstand wet conditions and prolonged flooding (Kent and Johnson, 2001). On the drier parts of the catena (i.e. the valley crests), *A. conyzoides, D. horizontalis*, *C. benghalensis* and *E. heterophylla* showed the highest relative frequency. Those dryland weed species were observed previously on the fringes of similar inland valley rice systems in the forest-savanna transition zone in Cote d'Ivoire (Johnson and Kent, 2002). Any causes that limit the opportunity to suppress weeds through flooding during the early crop stages, may result in a shift of weed communities from a community dominated by species adapted to flooded conditions to a community of species adapted to hydromorphic or upland conditions, such as *A. conyzoides*, *A. sessilis*, *B. decumbens*, *T. triangulare*, *P. scrobiculatum*, *D. horizontalis, S. nodiflora*, *L. decurrens*, *P. angulata*, *B. polystachyon* and *E. colona* (Akobundu, 1987). Since the valley bottoms dry out during the dry season, dryland weeds that are able to complete their life cycle on residual moisture thrive well in the inland valley ecology between two rainy seasons (Rodenburg et al., 2009).

4.1.4.4. Relation between weed species, environment and management factors

Climate was not a differentiating factor in the present study; there were no obvious climatic variations (temperature and rainfall) between the experimental sites which were in the same agro-ecological zone.

Previous studies have shown that soil characteristics can be important determinants of local weed seedbank and species occurences (Hanzlik and Gerowitt, 2011; Hawes et al., 2010). Soil analyses indicated an increasing percentage of clay content going from the valley crests to the valley bottoms. The upland weed species *I. cylindrica* was observed more frequently in sandy soils compared to clayey soils. This suggests that the growth of rhizomes and buds, a major means of regeneration of *I. cylindrica*, was not restricted under light-textured soils. Chikoye and Ekeleme (2001) observed a high abundance of *I. cylindrica* in sandy soils. *C. benghalensis,* and *A. spinosus* known as nitrophilous species were frequent on well-structured soils (sand content < 40 % and clay content <40 %) with high nitrogen content (Le Bourgeois and Merlier, 1995). The effect of clay content on weed species occurrence in this ecology is directly related to a higher water retention capacity and indirectly to an association between clay particles and nutrient and organic matter accumulation following deposition processes (Ogban and Babalola, 2009).

Various elements of cropping systems, i.e. rotations, soil preparation, cropping schedule and weeding techniques may influence weed species occurrences. Cropping systems and levels of intensification have been reported to impact on species composition. Kent et al. (2001) showed that *Cyperus iria* and *Sphenoclea zeylanica* were particularly abundant in intensified and bunded fields. They associated these weeds with sustained flooding and intensification, while *Cyperus rotundus* and *Cynodon dactylon* were associated with rice followed by dry-season vegetable cropping. In the present study, some species were absent on rice - fallow land with predominantly zero-tillage, but present in the intensive systems of the rice - vegetable and/or rice - maize systems. These species were *C. benghalensis*, *D. horizontalis*, *E. heterophylla*, *C. aestuans*, *I. aquatica* and *Cyperus sphacelatus*. With intensive cropping, the frequency of some of those species such as *C. benghalensis* increases from year to year, reaching a maximum infestation level after 10-15 years. This is an important phenomenon under intensive cropping systems involving tillage, with fertilizer and irrigation applications (Le Bourgeois and Marnotte, 2002). *Tridax procumbens* and *Cleome ciliata* were also frequent in the rice – vegetable (jute mallow and okra) systems where fertilizers are used. Farmers are willing to fertilize significantly dry season vegetables crops such as jute mallow and okra in order to increase the yields, because those crops attract higher market price during the dry season (Singbo and Oude Lansink, 2010). Also farmers used fertilizers on vegetables because of the smaller sizes of those fields compared to the rainy season rice fields. The smaller sizes of vegetable farms are explained by the more labour constraints associated with vegetables, and the existence of the price risk associated with uncertainties in marketing, particularly for perishable crops such as vegetables, and inefficiency of existing irrigation system to produce vegetables in conjunction with rice (Mahmud et al., 1994). Frequency of *T. procumbens* in arable fields has been associated with intensified crop production before, in northern Cameroon (Le Bourgeois and Merlier, 1995). In the current study, position on the catena seemed to be largely entangled with cropping systems; with okra being cultivated on the drier valley crests, and jute mallow being cultivated on the hydromorphic fringe and valley bottom positions. For the rice - fallow system, *B. decumbens*, *Mariscus alternifolius* and *B. polystachyon* were the most dominant. These weeds were favored by the minimum tillage operations practiced at Houinga site with no functional irrigation systems.

In integrated weed management, crop rotation is among several practices used as an indirect method of suppressing weed growth (Rodenburg and Johnson, 2009). Averaged across the three villages, the most dominant species were *C. rotundus*, *C. viscosa* and *P. oleracea* in dry season vegetable and *L. octovalvis*, *I. aquatica*, *S. zeylanica* and *C. benghalensis* in wet season rice. Most of those dominant weed species and others within the weed populations were found both in rice and vegetable crops. In our survey, dryland upland weeds were observed in lowland rice because of inadequate flooding in the rice crop due to scarce rainfall and inadequate irrigation. Akobundu (1987) and Rodenburg et al. (2009) reported the presence of upland weeds in rainfed lowland rice due to inadequate flooding in the rice crop. In the present study, weed pressure in term of soil coverage was rather similar in the wet season rice and dry season vegetables. The improved lowland rice varieties in our survey were semi-dwarf type with narrow and erect leaves. Such varieties presumably have low weed competitiveness (Zhao et al., 2006). Jute mallow was broadcast at the optimal seeding density but also had an erect growth habit. Frequent leaves cutting for home and market consumptions considerably reduced the leaf area for shading weeds. Okra was direct seeded in rows at 75 × 35 cm. The leaves are arranged spirally, and are variable in shape and size. The wide spacing combined with its leaves structure and erect growth habit reduces its competitiveness against weeds (Hamma et al., 2012). Tuberous roots vegetable sweet potato (*Ipomoea batatas* L.) cultivar with large leaf area and growth habit with spreading canopy structure and high plant density was used as means to reduce weed infestation in Southern Ethiopia (Workayehu et al., 2011). Some weeds were not notably affected by the different environmental conditions imposed by the position on the upland-lowland continuum; the relative frequencies and coverage rates of *A. conyzoides*, *S. nodiflora*, *D. horizontalis*, *S. monostachyus*, *R. cochinchinensis*, *P. polystachyum*, and *P. angulata* were similar throughout the catena. All those weeds were therophytes and the two grasses (*D. horizontalis* and, *R. cochinchinensis*) had C_4 photosynthesis pathway. These seem to be species with high ecological plasticity and therefore potential problem species with high adaptability. This is also an indication that they might become serious weeds in other situations into which they could potentially be introduced (Tamado and Milberg, 2000).

In a study conducted in the lowland fields in the savanna zone of Cote d'Ivoire revealed that the differences in species composition could be explained largely by difference in water management and hydrology, rather than by cropping systems (Kent et al., 2001). In the Tibetan plateau of India with a very different ecology from our study site in terms of altitude, topography and climate, topography and soil moisture were found to be the most important environmental factors influencing the weed community composition (Dvorsky et al., 2011).

4.1.5. Conclusion

This study has identified major problem weeds along the upland-lowland continuum of inland valleys typically found in the southern Guinea Savanna zone. The differences in weed community compositions were explained largely by the hydrological gradient along the catena and to lesser degree by the cropping systems. Most of those weeds were annuals and had high ecological plasticity growing under a range of different hydrological conditions, ranging from freely draining uplands on the valley crests to the saturated and temporarily flooded valley bottoms. Weed management in inland valleys should prioritize these species with a large ecological plasticity and pay attention to these species as they may become more dominant or are more difficult to control in this ecology where flooding cannot, or only partially, be controlled. Prioritizing suitable weed control technologies targeted to these problem weeds of the weed communities of rice based production systems along the inland valley catena in the southern Guinea Savanna will unveil the production potential of this ecology.

4.2. The dynamics of arable weed communities under different management practices in inland valley of the Mono Couffo regions of Benin

4.2.1. Introduction

Pressure on land and soil resources due to a rapidly growing population is a severe problem across West Africa. In some regions, arable land has become scarce, and soil degradation and severe weed infestation continue due to the shortening of the fallow period (Akobundu et al., 1999; De Rouw, 1995). With the ongoing climate change, the availability of water is likely to decrease in the region, which will aggravate the difficulty of rain-fed agriculture (Rodenburg et al., 2011). Where severe weed infestation, soil degradation and water scarcity have occurred, successful agriculture requires intensified exploitation or expansion into alternative cultivation areas. Inland valleys might represent such an alternative in some areas due to their higher water availability, lower soil fragility and higher fertility compared to upland areas (Giertz et al., 2012). The extent of slopes uses is likely to intensify weed growth dynamics, water and nutrients fluxes and thus to differentially impact fertility and crop productivity (Bognonkpe, 2004). Besides indirect weed control practices (land preparation, planting methods, etc.), rice farmers in West African inland valleys mainly rely on hand weeding and to lesser extent on herbicides (Rodenburg and Johnson, 2009). The introduction of intensive farming methods in inland valleys resulted in substantial changes in arable weed communities (Kent et al., 2001). In some inland valleys, herbicide-susceptible weed species were reduced, while more herbicide-resistant species appeared (Rodenburg and Demont, 2009). An indirect effect of the use of herbicides was that weed control was no longer regarded as a function of tillage, and consequently from plowing to minimum tillage (McCloskey et al., 1996). The most widely reported effects of these changes of farming practices is the reduction in broadleaved weed species and an increase in the importance of grass weeds (Kent et al., 2001; Mathieu, 2005).

Weed management practices continue to change, and so do the weed communities. For example, intensive cereal-based cropping systems of the Southern Guinea savanna can result in weed problems (Rodenburg et al., 2009). It would be helpful in the design of farming systems to be able to predict how weed communities may change under diverse weed management practices. Our approach is to try to identify those characteristics which allow a particular weed species to thrive during the cropping cycles under a given set of management practices. It was thought that arable weeds in general could be distinguished from other plant species by a suite of characteristics which conferred the ability to persist in the arable ecosystem. These characteristics include growth cycle, high seed output, seed dormancy and rapid germination (Akobundu, 1987).

Small-scale farmers may cope with weeds by changing cropping practices and by weeding sessions. However, labor is not readily available, and is particularly in short supply at the start of the cropping season and at the harvest time of staple food crops. In these farming systems, much of the labor force, management, and capital originate from the household or production unit (PU) involving several players (PU head, wife or wives, one or several offspring, etc.) who run different sets of fields (Dounias et al., 2002). Therefore, the labour requirement taking into account the production unit concepts for weeding is used to explain the change of the weed communities.

It is hypothesized that within a set of fields of rice based systems distributed along the heterogeneous catena, the weed management practices, related yield losses and labour requirement will be largely influenced by the production units and related farming systems. The objective was to identify and characterize farmers' weed management practices and determinants, and to prioritize the research needed to develop appropriate weed management methods for rice based cropping systems in inland valleys at different stages of intensification linked to the production units.

4.2.2. Materials and methods

4.2.2.1. Study sites

The study was conducted during the 2010 and 2011 cropping seasons in three valleys, near the villages Agbedranfo, Vovokame and Houinga, in the departments of Mono (1860 km^2) and Couffo (2250 km^2) in south-western Benin, West Africa. The study sites are located in southern Guinea Savanna zone of West Africa, characterized by a bi-modal rainfall regime (Windmeijer and Andriesse 1993). A detailed physical characterization of the study sites is presented in Table 3, and sites selections criteria are stated in paragraph 3.5.1.1.

4.2.2.2. Survey

Information and data on farmers, production unit and crop production were obtained in surveys, including interviews with 45 farmers, observations of their practices, and measurement of labour input and crop yield on their plots. Records of land preparation and weeding labour were recorded at the three sites during the rainy season. Data on major environmental factors and crop management practices believed to influence the weed flora in general in each field were collected by observation (soil type, topography, type of crop), interviewing farmers (number of plowings before planting, date of planting, fertilizer use, number and date of weeding. Environmental and crop management variables of nominal type (soil type, topography, crop type, fertilizer and herbicide use) were converted into qualitative binary dummy variables that take the value 1 if the field belongs to the category or 0 if it does not. Number of plowings, date of planting, number and date of weedings and rainfall were quantitative variables and hence measured on an interval scale. Specifically for quantitative data concerning weeding operations, on each day, the total time workers spent on the field and the working time were recorded with a stopwatch, and the area they weeded was measured. Time records were made for all workers separately. As workers weed in any direction, it was impossible to measure the area an individual weeded in one day. That is why only the total weeded area at the end of the day was surveyed. Children were accounted for half adult, and in addition no distinctions were made between male and female workers, although weeding in vegetable crincrin was a predominantly performed by women. For weeding operations of rice and okra, the involvement of men was common.

The main field research activities were descriptive and explorative surveys and vegetation sampling on transects along the catena from the valley crest through the hydromorphic fringe to the valley bottom during two campaigns from 2010 to 2011. Weeds were sampled in 45 farmers' fields with rice, jute mallow, okra or maize as main crops, along transects using two randomly placed quadrats of 6 m^2. The size of each farmer's field was between 400 and 2400 m^2, and each field represented one repetition with averaged value of the two quadrats. Percentage soil coverage (the ground area covered by the vertical projection of above-ground plant parts) was estimated visually for each of the weed species in each quadrat and scored on a scale from 0 to 9 (0: absence; 1: 1%; 2: 7%; 3: 15%; 4: 30%; 5: 50%; 6: 70%; 7: 85%; 8: 93%; 9: 100%) (Marnotte et al., 2004). The mean weed coverage was calculated as the ratio of the sum of weed coverage scores over the total number of points of sampling. Weeds were identified and described at the genus and species level according to illustrated handbooks of Akobundu and Agyakwa (1987), Johnson (1997) and a tool for computer aided identification (IDAO) for weeds of rice in Africa (Grard et al., 2013). Unidentified weeds in the field were tagged, pressed and identified in the herbarium of the University of Abomey-Calavi. Biology of the weed species was determined from previous studies (Akobundu, 1987; Akobundu and Agyakwa, 1987; Grard et al., 2013; Johnson, 1997; Le Bourgeois and Merlier, 1995).

Crop yield (only rice) was measured in two quadrats (1 x 1 m). Rice grain yield was corrected to 14% moisture content.

4.2.2.3. Data analysis

Survey data were encoded and frequency tables made using spreadsheet software programs. Statistical analyses were accomplished using SAS software (SAS Institute, 2004). Both parametric and non-parametric test were conducted. For quantitative data, Fischer test (F) was used, while for qualitative data, chi-square test was used.

To describe the effects of interactions of the production units and farming systems, and farmers' weed management methods, the data were subjected to principal component analysis (PCA). This ordination method seeks to detect the patterns of variation in the farmers' weed management methods data that are best explained by the production units and farming systems variables provided. The production units, farming systems and the weed management methods were evaluated using a binary decision rule (observed/not observed). The analysis was performed using the procedures in CANOCO software, as recommended by Ter Braak and Smilauer (1998). The ordination is plotted as a farmers- production units, farming systems and the weed management methods biplot with scaling focused on interfarmers' distances. As weighted averages of the farmer's scores, those scores are located at the centroid of the farmers in which they occur; thus each farmer is located at the center of its niche in the ordination. Nominal variables (i.e. production units, farming systems and the weed management methods) are represented by arrows). One form of output from this analysis is the farmers-nominal variables biplot on which the positions of the farmers with respect to the ordination axes are depicted along with arrows showing the direction of the greatest variability of nominal variables. The strength of the relationship between a variable and a farmer is depicted by the length of the variable' (right angle) projection onto the arrow or its extension. The eigenvalues (λ) were used to measure how much variation in farmer data was explained by the nominal variables.

4.2.3. Results

4.2.3.1. Weed management practices of farmers

There are five different weed management (WM) strategies in the areas based on cropping seasons and crop types (Table 10). During the rainy and dry seasons, they include cultural methods (slashing standing vegetation, patchy burning before crop planting, practices of land preparation, planting, weeding sessions and other cultural practices) (Figure 23). Specifically during the rainy season when lowland rice was grown, chemical methods based on herbicides were used (Figure 24). WM2 is based mainly on no-tillage planting and the use of the systemic total herbicide glyphosate. The other two methods (WM1 and WM3) are based on land preparation. For rice, the first weeding in WM1 and WM2 involves hand hoeing, while in WM3, some selective herbicides are used in order to save labor. The second weeding for the three methods involves hand hoeing. The third weeding was optional, and not all farmers weed a third time.

Table 10. Weed management methods used by farmers in monitored fields.

Cropping season	Crops	Weeding method	Land preparation	Planting	First weeding	Second weeding	Third weeding	Additional weeding	Herbicide uses
Rainy season	Rice	WM1	Patchy residues burning + manual tillage	Direct seeding + transplanting in line	Hoeing	Hoeing	May be done	None	None to few
	Rice	WM2	None to few	Transplanting in line	Hoeing	Hoeing	None	None	Total herbicide
	Rice	WM3	Patchy residues burning + manual/mechanical tillage +/- total herbicide	Direct seeding + transplanting in line	Hoeing + few selective herbicide	Hoeing	None	None	Selective herbicide with few total herbicide
Dry season	Jute mallow	WM4	Patchy residues burning + manual tillage	Broadcast	Hand pulling	Hand pulling	Hand pulling	Up to 5 weeding	None
	Okra/maize	WM5	Patchy residues burning + manual tillage	Line seeding	Hoeing	Hoeing	May be done	None	None

During the dry seasons with mainly three vegetable crops (jute mallow, okra and maize) were grown. For jute mallow, hand pulling weeding was done up to five times, whereas for okra and maize, hoeing was done mainly twice.

On the three sites, row or line planting was the common planting methods for the cultivated crops, except jute mallow which was broadcast by the farmers without any consideration concerning the optimal seed density. Also for most row seeding cases, most farmers tended to overplant, and only few thinned later the plants.

Dry seeds were directly sown without soaking or pregermination in rows for rainy season lowland rice and dry season vegetables, and transplanting was usually done in rows for lowland rice with 21- to 30-day-old rice seedlings, although often much older.


Slashing with cutlass


Cutting back sprouting grasses with hoes


Drying fallow vegetation


Burning of slashed vegetation


Patchy burning spots


Manual tillage with hoes

Figure 23. Cultural manual weed management methods.


Drilling rice seedlings holes along seeding cords


Rice transplanted in line


Hand hoeing rice


Hand pulling weeds from rice


Hand pulling weeds from jute mallow


Hand hoes for weeding rice, okra and maize

Figure 23. (Continued)

Total and selective herbicides

Spraying total herbicide glyphosate

Imperata cylindrica herbicided by glyphosate

Rice planted in total herbicided no tilled plot

Figure 24. Chemical weed management methods.

The two weed management methods during dry season were quite uniform among farmers during the dry season, consisting of hand pulling for jute mallow, and hoeing for okra and maize. Thus weed management methods during the dry season analysis will not be discussed extensively; rather emphasis will be put on the weed management methods of lowland rice during the rainy seasons which were more diverse.

Hence the major weed management method, hand weeding was applied by all farmers in the three villages studied (there was no significant difference) (Table 11).

Table 11. Hand and chemical weed management practices of farmers, rainy season 2010-2011.

Weeding methods	Agbedranfo n =18	Houinga n = 14	Vovokame n = 13
Hand weeding (n)	18^a	14^a	13^a
Total herbicide (n)	0^b	12^a	0^b
Total + selective herbicide (n)	9^a	2^b	0^b
Mean number of sprays	2.0^a	2.2^a	0^b
Mean number of products	1.1^a	1.2^a	0^b

^{a,b} Different letters in rows indicate a significant difference ($P \leq 0.05$) .

Total herbicide was solely used by 12 of 14 farmers at Houinga, whereas the combined herbicide (total + selective) was used by 9 out of 18 farmers at Agbedranfo and 2 out of 14 farmers at Houinga. There was no herbicide use at Vovokame. Farmers applying herbicides spayed on average twice, and mainly using one product. Herbicides comprised mainly total herbicide (glyphosate) for controlling perennial grass weed such as *Imperata cylindrica*. Selective phenoxy herbicide (2,4-D) was also used by some rice farmers for controlling mainly broadleaved weeds (e.g. *Ageratum conyzoides*, *Eclipta prostrata*, *Ludwigia octovalis* and *Sphenoclea zeylanica*), and sedges (e.g. *Cyperus difformis* and *Fimbristylis littoralis*). As the water supply was unreliable at Houinga which used most of the herbicides but did not have irrigation infrastructures, herbicides performances were poorer and yields were lower than at Agbedranfo, and farmers that used them tended to use lower standard application methods. Glyphosate application rate ranged from 0.45 to 0.75 kg active ingredient (a.i.)/ha. The recommended rate range was 1.5-3.0 kg a.i./ha with an average of 2.3 kg a.i./ha. Thus, they were applying from 67 to 80% less than the recommended rate. 2,4-D application rate ranged from 0.21 to 0.52 kg active ingredient (a.i.)/ha. The recommended rate range is 0.5-1.5 kg a.i./ha with an average of 1 kg a.i./ha. Farmers were applying from 48 to 80% less than the recommended rate. When applying herbicides, the farmers used less than 100 to more than 300 liters water/ha, with an average of 200 liters/ha. For good weed coverage, 400 liters/ha is recommended.

4.2.3.2. Reasons indicated by farmers for weeding methods

The major significant differences among farmers' weeding methods were based on agronomic reasons relating to burying the weeds, efficiency of weed control, and timely land preparation, as well as on unknown other reasons (Figure 25). The final choice is determined by farmers' resources endowments (labor, herbicides, etc.) and biophysical conditions in the field (types of weeds). For WM1 relying mainly on hand weeding, burying the weeds was the major reason, while for WM2 and WM3 using herbicides, timely land preparation and better weed control were the major reasons (Figure 25).

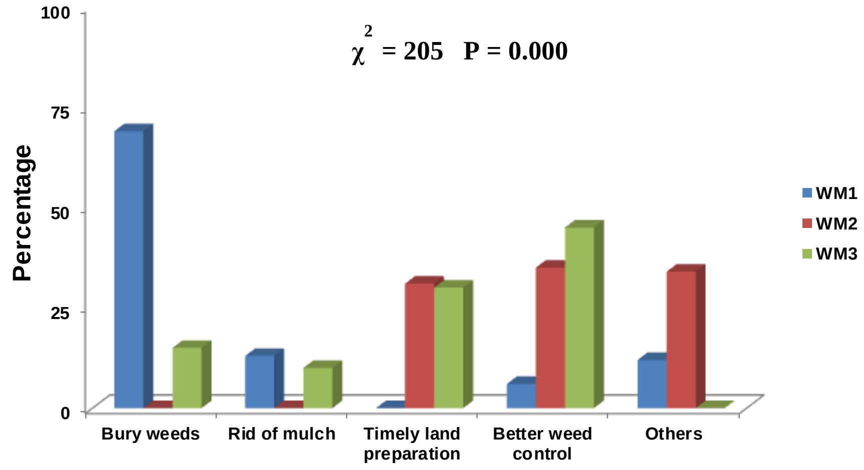


Figure 25. Reasons indicated by farmers for weeding methods in the three study villages, rainy seasons 2010-2011.

4.2.3.3. Weed management practices at the three sites

During the rainy season, the use of the different weeding methods was different significantly across the three villages, with a preference of Vovokame and Agbedranfo for WM1, Houinga for WM2, and Agbedranfo and Houinga for WM3 (Figure 26).

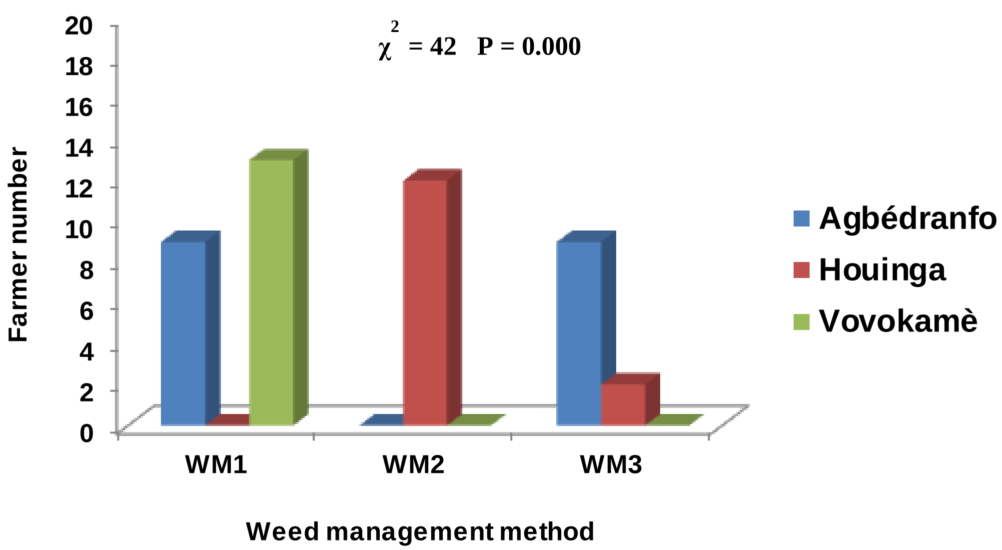


Figure 26. Weed management practices at the three sites, rainy season 2011.

Farmers in Houinga preferred WM2 with the application of the non-selective, translocated total herbicide glyphosate against both annuals and perennials, because they tried to reduce labor-requirements for land preparation through no-tillage (Figure 24).

4.2.3.4. Weed management practices of the different cropping systems

The different cropping systems were entangled by the village sites factor. There were significant differences between the different cropping systems according to the weed management methods (Figure 27). Farmers practicing the rice-jute mallow (Agbedranfo) and rice-corn (Vovokame) systems preferred WM1, while farmers practicing rice-fallow system (Houinga) relied on WM2, and farmers practicing rice-okra (Agbedranfo), rice-okra (Agbedranfo) and rice-fallow systems were linked to WM3.

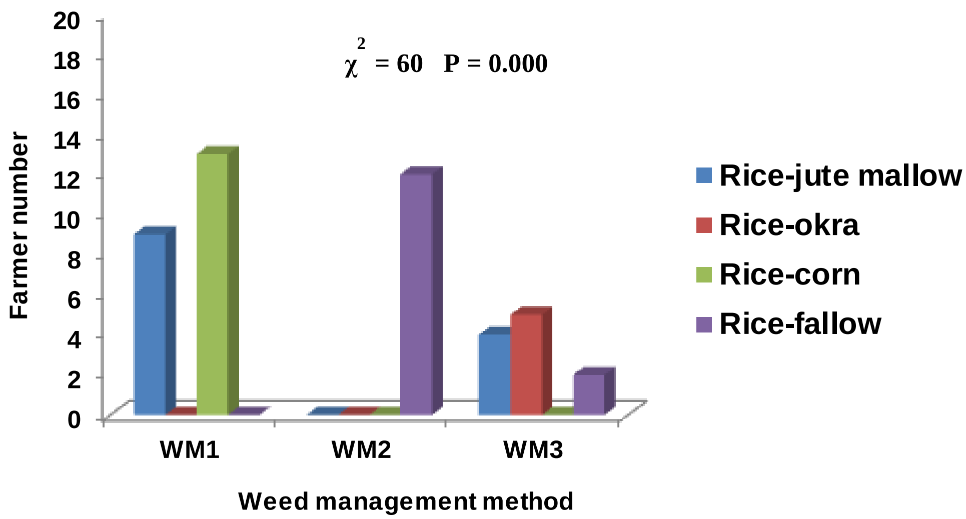


Figure 27. Weed management practices of the different cropping systems, rainy season 2011.

4.2.3.5. Weed management practices at different catena positions

There were no significant differences between the different catena positions according to the weed management methods (Figure 28). However, hydromorphic fringe position farmer numbers were higher for the different weed management methods than the other farmers at the crests and valley bottom positions.

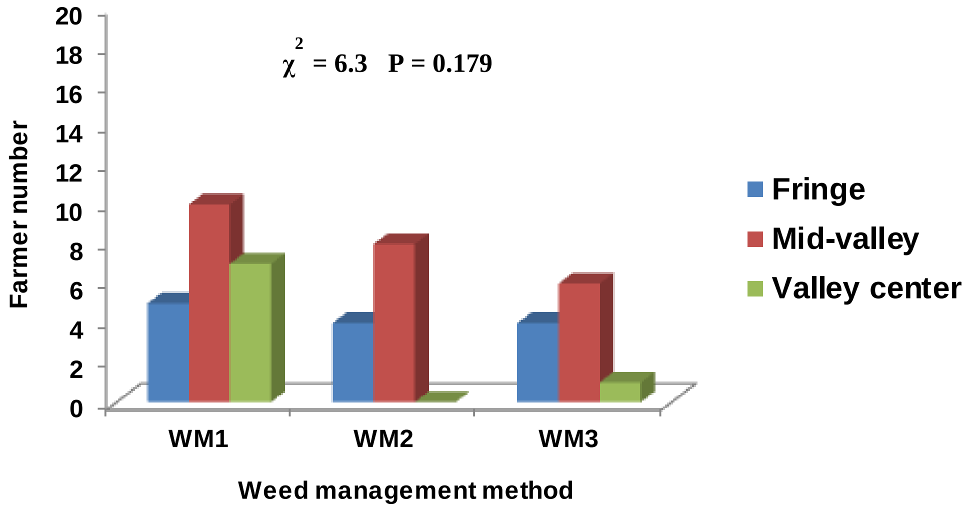
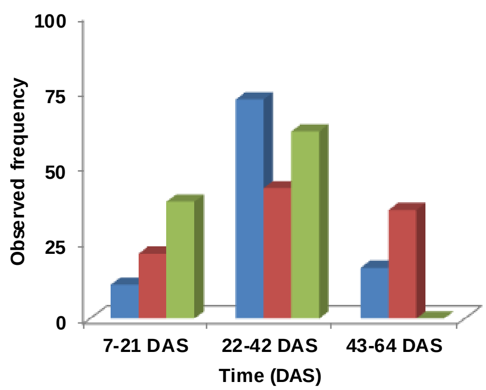


Figure 28. Weed management practices at different catena positions, rainy season 2011.

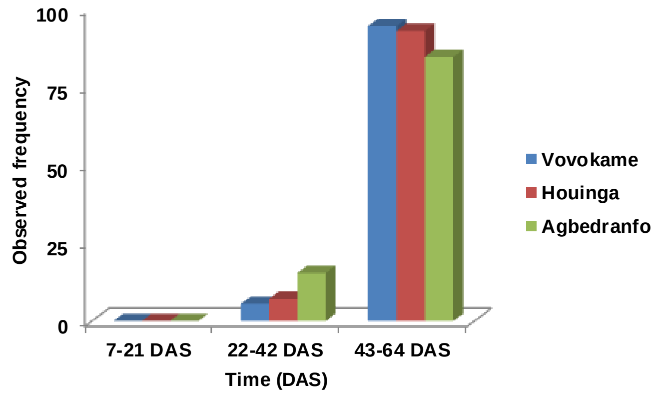
4.2.3.6. Timing of weed management practices

For rainy season rice, weeding was done mainly twice at the three sites by most of farmers: the first weeding was done within 21 days after seeding (DAS) and the second weeding at 43 to 64 DAS (Figure 29). 39%, 22% and 11% of farmers respectively at Agbedranfo, Houinga and Vovokame carried out this first weeding during the time period of 7 to 21 DAS, because they considered this first weeding as essential for obtaining a reasonable yield. Then the bulk of farmers (72%, 43% and 62% of farmers respectively at Agbedranfo, Houinga and Vovokame) weeded their fields at 22 to 42 DAS. For the second weeding, 85%, 93 and 94% of farmers weeded between 43 to 64 DAS. These first and second weedings were carried out mostly by women, and sometimes they involved men and children as well.

A



B



Chi square test	Vovokame	Houinga	Agbedranfo
Cochran's Q	12.333	1	7.538
P level	0.002	0.607	0.023

Chi square test	Vovokame	Houinga	Agbedranfo
Cochran's Q	30.333	22.429	15.846
P level	0.000	0.000	0.000

Figure 29. Timing of first (A) and second weeding (B), rainy seasons, 2010-2011.

During the weeding, farmers tilled the soil superficially and cut back the weed species with a short hoe. Sometimes, weeds were uprooted with hand (hand pulling). Although farmers were aware that a third weeding favored the development of rice crop, not all of them weeded a third time. Mainly at Houinga site, some farmers practicing minimum tillage using the systemic herbicide glyphosate, sprayed the chemical two to three weeks before planting. Supplemental hand weeding sessions took place in order to remove weeds species that were not reached by the herbicide, because they were covered by other vegetation at spraying.

During the dry season, timing of weed management was quite identical for the surveyed cultivated crops. For the broadcast seeded jute mallow system, it was difficult to enter and to weed the fields without damaging the plants. Hand pulling was the only weed control method applicable, because the spatial arrangement made hoe weeding difficult, and the farmers had little or no knowledge of chemical weed control. The first weeding was done within three weeks of seeding by all farmers, and at every 2 weeks before harvest consisting of cutting leaves for sale on local markets. Thus at least four weeding sessions were done by farmers.

Okra was weeded by all farmers at least twice. The first weeding was done within three weeks of seeding by all farmers, and at every 25 days.

Corn was weeded by all farmers at least twice. The first weeding was done within three weeks of seeding by all farmers, and at every 15 days.

4.2.3.7. Evolution of weed cover under management practices during dry season

In 2010 and 2011, after land preparation and seeding operations, AD's jute mallow field had low levels of global weed cover (Figure 30 A). The first weeding operations started at around 15 DAS, and then two weeding sessions are performed each two weeks following the revolving market days (each five days) of the different surrounding cities, regardless of the global weed covers. On the eve of market days, many women can engage in a type of unpaid exchange weeding of particular crincrin fields in anticipation of harvesting the fresh leaves to be sold at the market. After the third weeding, leaves harvesting took place without weeding the fields. Concerning the weed species and the global weed coverage, weeding operations were less effective in 2010 than in 2011, and *Cyperus rotundus* appeared to be less affected by the land preparation, seeding operations and the first weeding operation in 2010; its coverage reached 20% before 20 DAS (Figures 30 B, 30 C and 30 D).

The global weed covers for other selected dry season farmers are listed in the Appendix B.

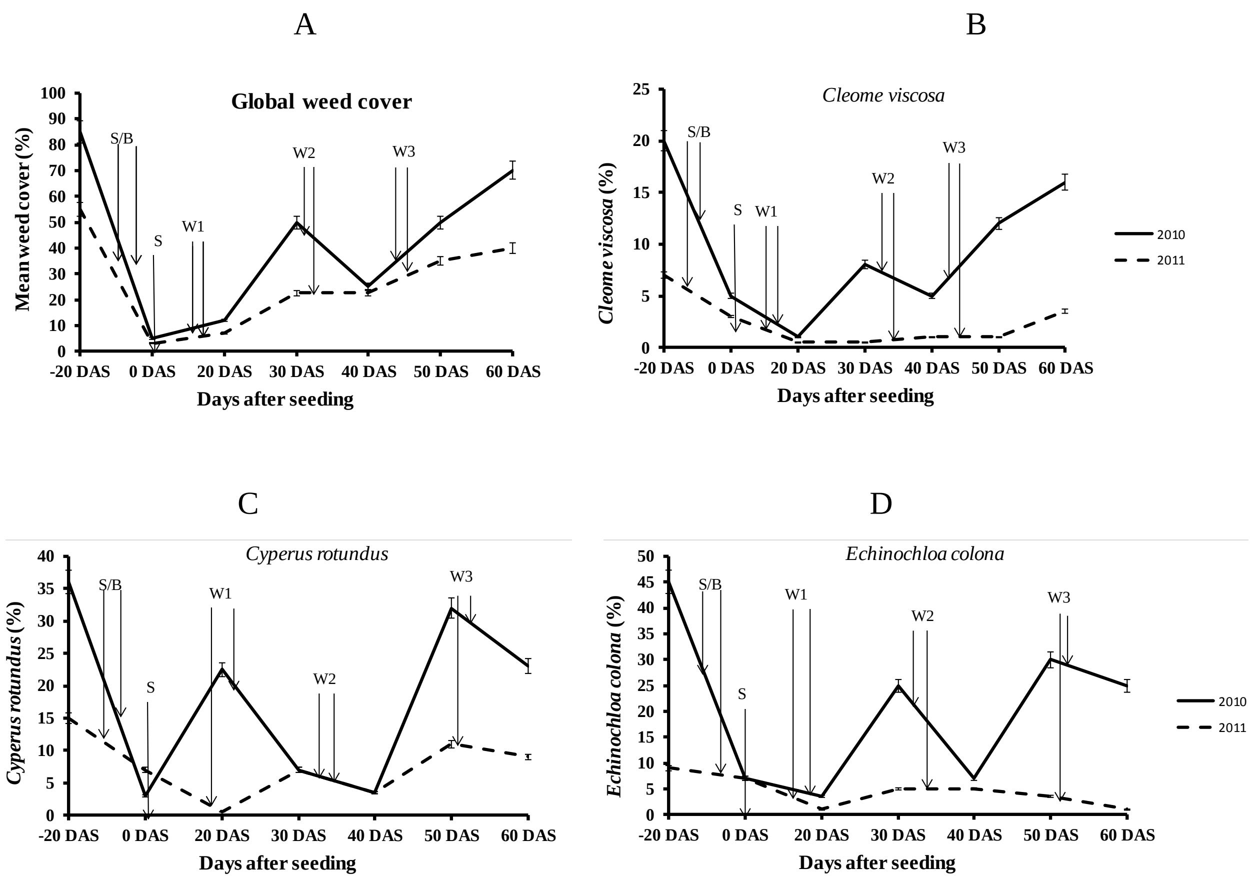


Figure 30. Evolution of weed coverage under jute mallow in the field of AD at Agbedranfo (2010-2011) (S/B= slash/burn; S = seeding; W1=first weeding; W2= second weeding; W3= third weeding).

Okra fields were not weeded more than three times, and the weeding operations were performed by women and/or men. Concerning the weed species and the global weed coverage, weeding operations were less effective in 2010 than in 2011 (Figures 31 A, 31 B, 31 C and 31 D). For TG's okra field, the first weeding was done with global weed cover under 15% at 21 DAS for the two years (Figure 31 A). In 2011, the threshold lied about 40% global weed coverage for the start of the second weeding operation. As vegetables were grown during the dry season, and also considering the fact that farmers had full access to irrigation water (all-year round water availability), recent fallen rainfall amount was not a determining factor to start weeding.

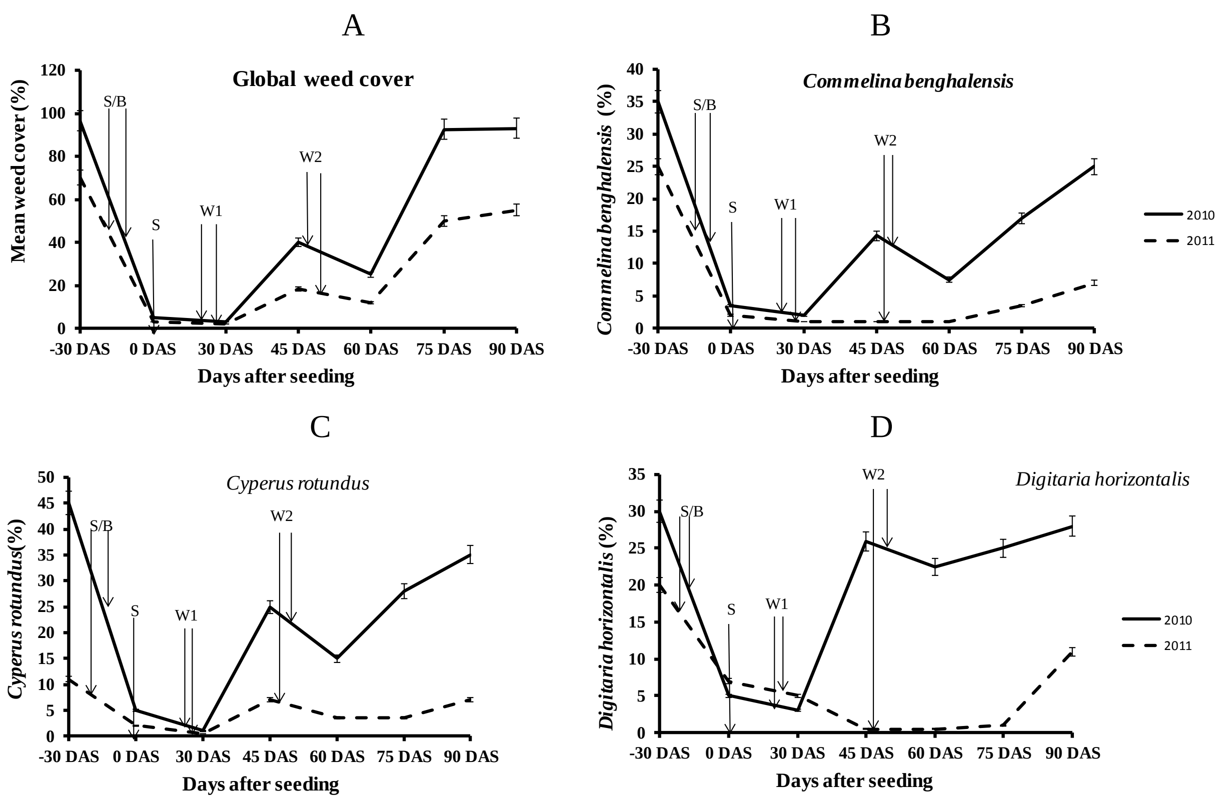


Figure 31**.** Evolution of weed coverage under okra in the field of TG at Agbedranfo (2010-2011) (S/B= slash/burn; S = seeding; W1=first weeding; W2= second weeding).

In 2011, *Digitaria horizontalis*, *Cyperus rotundus* and *Commelina benghalensis* were less affected by the first weeding operation, and their coverages rose between 15- 25% at around 45 DAS (Figures 31 B, 31 C and 31 D).

AD's maize field had low levels of global weed cover, especially during the early vegetable crops growth stages (Figure 31 A). Weed covers continued to remain below 15% for major weed species (*Ludwigia hyssopifolia*, *Eclipta prostrata*, and *Panicum laxum*) up to the first weeding at 30 DAS (Figures 32 B, 32 C and 32 D). The intensification of lowland use with values added crop such as maize in the study area has generally resulted in increased efforts by farmers towards maximizing the productivity of the scarcest resource, i.e., per unit area through intensive crop husbandry, maintaining weeds cover at low levels.

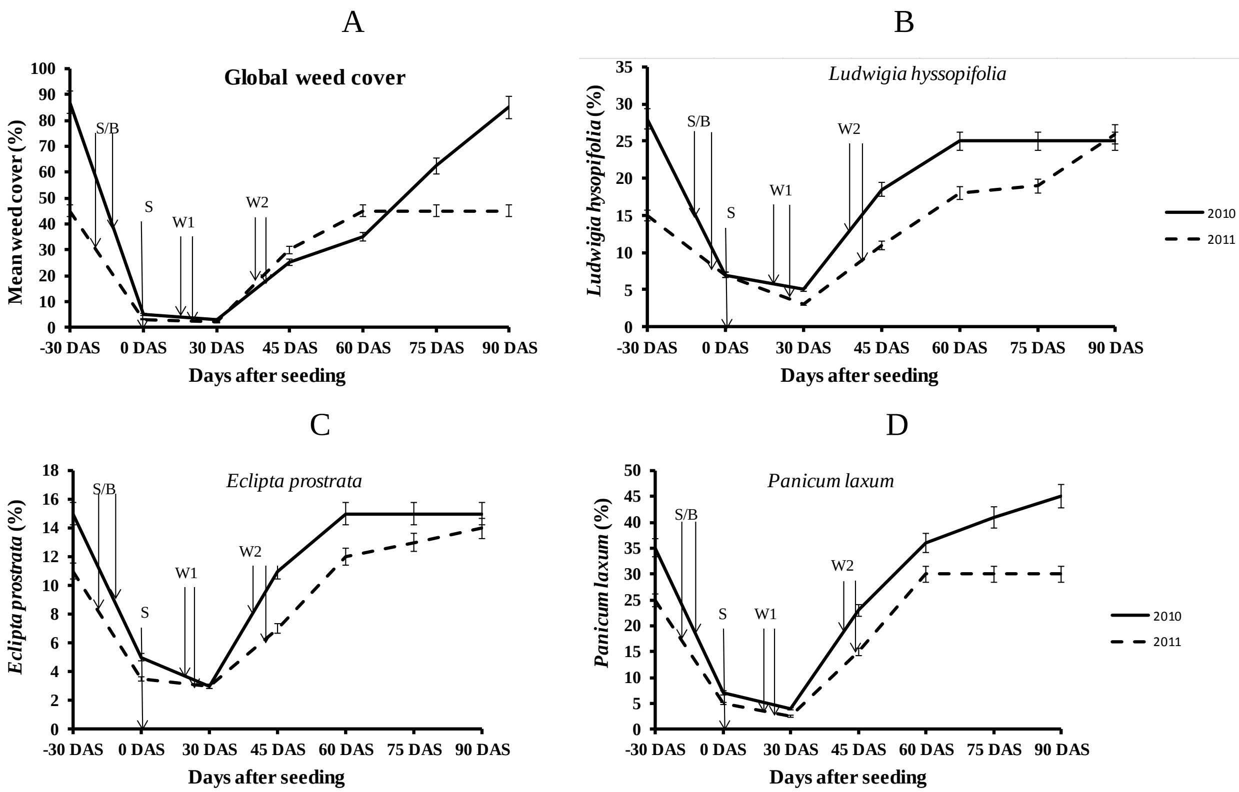


Figure 32. Evolution of weed coverage under maize in the field of AD at Vovokame (2010-2011) (S/B= slash/burn; S = seeding; W1=first weeding; W2= second weeding).

Although farmers knew that the second weeding favored the development of maize and gave better access at harvest, not all of them weeded a second time. For few who weeded twice at around 45 DAS, this weeding consisted of less elaborated cutting of weed regrowth with a cutlass; thus this weeding did not smother major weed species and coverages (Figures 32 A, 32 B, 32 C and 32 D).

4.2.3.8. Evolution of weed cover under management practices during rainy season

For SM's hand weeded rice field, from seeding to the first weeding at around 21 DAS, weed coverage was below 15% (Figures 33 A, 33 B, 33 C, 33 D and 33 E). Then the weed cover increased significantly to reach 40 and 50% in 2010 and 2011 at 56 DAS (Figure 33 A). That relative inefficiency of the weeding at that period was that weeding was often delayed due to labour pressure at the beginning of the rainy season, when upland and lowland preparation preparations, planting, and weeding all compete for the farmers' limited labour. As the season advanced through the critical reproductive and ripening phases of the rice plants, coinciding with the harvest period of the staple maize crops (labor availability issues). Then the second weeding decreased significantly the weed cover until 84 DAS, and no third weeding took place

The global weed covers for other selected rainy season farmers are listed in the Appendix C.

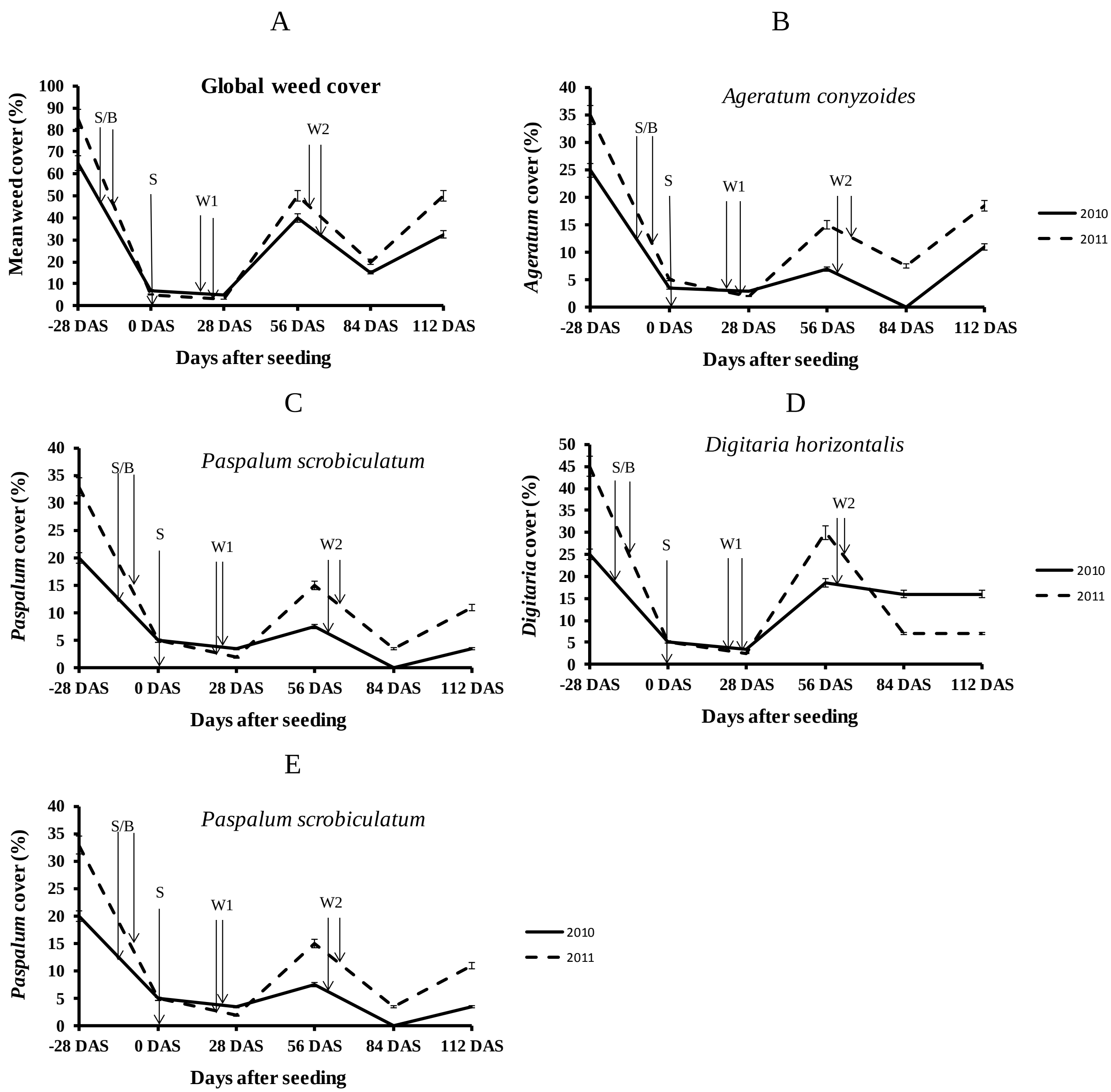


Figure 33. Evolution of weed coverage under rice in the field of SM at Agbedranfo (2010-2011) (S/B= slash/burn; S = seeding; W1=first weeding; W2= second weeding).

At Houinga in DP's rice field, total herbicide (glyphosate) application decreased significantly the global weed covers and covers for dominant species such as *Imperata cylindrica*, *Paspalum scrobiculatum*, *Ageratum conyzoides* and *Synedrella nodiflora* (Figures 34 A, 34 B, 34 C, 34 D and 34 E). Additional first hand weeding was done at around 28 days after transplanting (DAT).

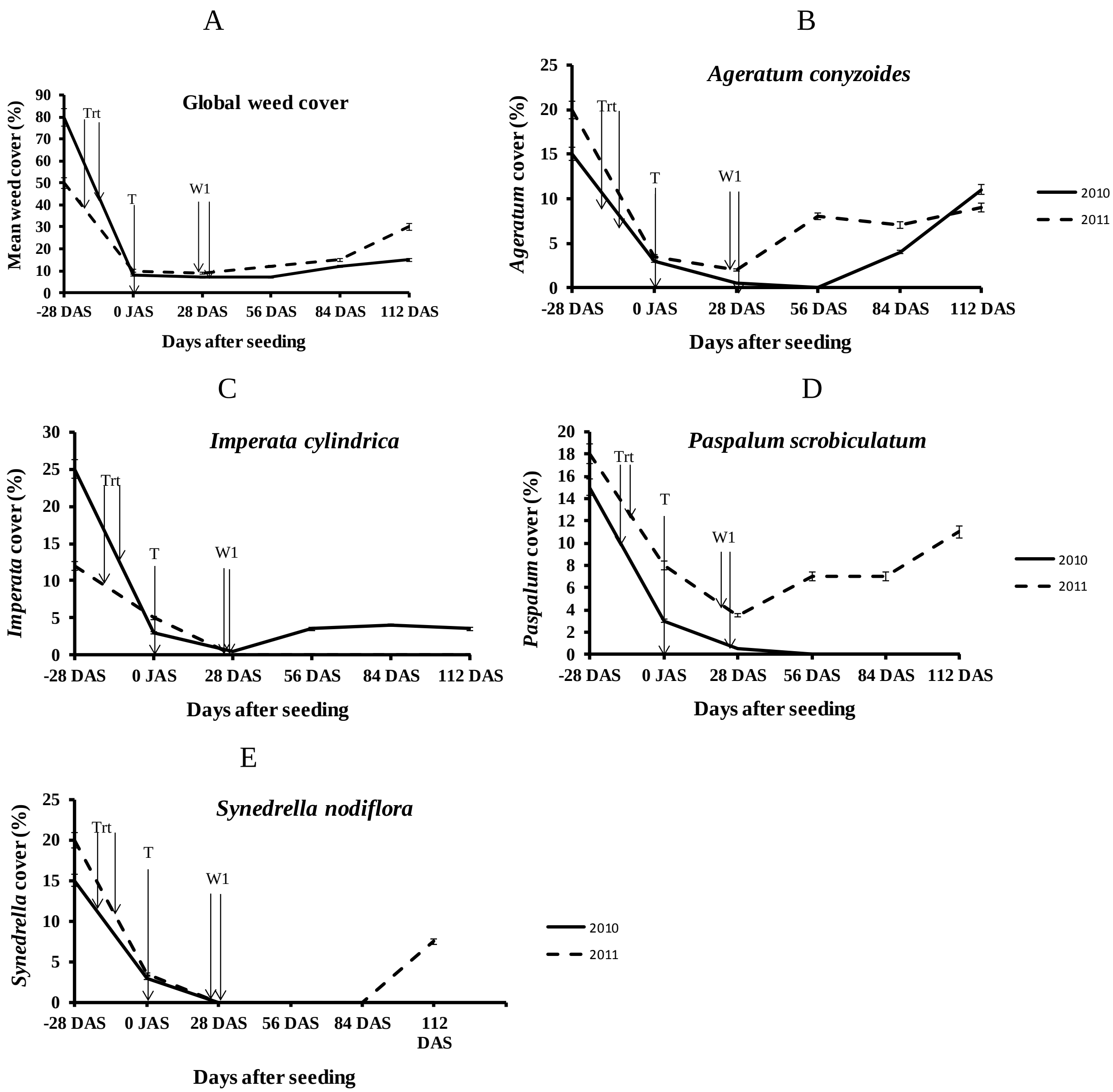


Figure 34. Evolution of weed coverage under rice in the field of DP at Houinga (2010-2011) (Trt=application of glyphosate treatment; T= transplanting; W1=first weeding).

In 2011, the herbicide application was not particularly effective in smothering *Paspalum scrobiculatum* and *Ageratum conyzoides* which covers increased to reach 8-10% respectively at around 56 DAS. No third weeding took place.

In West African inland valleys, the bulk of agricultural production including weeding management practices is undertaken by small-scale farmers whose labor force, management and capital originate from the households or production units.

4.2.3.9. Characteristics of production units and farming systems

The hierarchical classification using Ward's minimum-variance method allowed the *a priori* typology of the production units and farming systems based on the study of characterization of the lowlands of Agbedranfo, Vovokame and Houinga (Assogba et al., 2011). In this study, the set of criteria or diversity variables are grouped into four categories: demographic and socio-economic variables; systems activities variables; variables related to productive resources and those related to cultivated fields in the lowlands.

4.2.3.9.1. PU1 Dominantly part time farmers with casual employment

These are production units based on off-farm activities and 21% of the surveyed samples belonged to this production unit. They are the least equipped with productive resources: exploitable and cultivated areas in various agro-ecological zones, in labor (low family labor (2.3) and not use paid labour), no special equipment. Productive resources are very limited with very small field sizes in developed lowland (150 m^2). These farmers have no exploitable land on undeveloped lowlands. Resources limitations orient those farmers towards off-farm activities. The average number of activities (3.86) and the pluriactivity intensity (3.69) are high. Agricultural activities and trade are the two main activities (71%). The diversification of activities comprises the processing and casual labour (43%). As a result, agriculture does not occupy a very important place in the system of activity. The majority of these farmers are women (93%), relatively young (33 years) without any level of education (64%) and not having received any training in rice or vegetable production (64%). The size of the households is also relatively small (5.2). Fertilizers are the only chemical inputs used, thus reflecting a low level of intensification.

4.2.3.9.2. PU2 Dominantly in undeveloped lowlands

This production unit is dominant in undeveloped lowlands and is represented by 27% of the sample surveyed. These farmers have relatively large fields on undeveloped lowlands (3500 m²). The availability of family labour is the largest (4 members). They have no specialized equipment or tools and 72% do not use paid labour. Farming activities has therefore a greater share of their activities. The average time spent on these farming activities is 61.8% and their contribution to the total income is located at 53% on average. The trade and quartz gravel stones mining are the second and third main activities. The activity system is somewhat diversified (3.56) and the pluriactivity intensity is low (3.07). 78% and 44% of farmers use fertilizer and herbicide respectively. The level of intensification is therefore higher than that of type 1. 57% of the rice production is for market. The farmers are mostly female (83%) and older (46 years on average), without any level of education (94%). The household size is also larger (6.8 members).

4.2.3.9.3. PU3 Dominantly farmers with significant resources and strong capacity for investment

This production unit concerned dynamic farmers with significant resources and a strong capacity for investment in agricultural activities, and represented 15% of the sample. They have farms in all agroecological zones with relatively high areas and 3.6 agricultural active people. They are in a dynamic of expansion of inherited or borrowed cultivated lowlands (0.69 ha), purchased or leased (0.79 ha). Cultivated areas in the undeveloped lowlands are 9300 m² in average. 90% of farmers have motor pumps and water hoses for irrigation purposes and use paid labour (40%). These are the farms with the highest level of intensification: 100% of farmers use fertilizer and pesticide and 10% of farmers use herbicide. Vegetable productions are marketed at 85%. The activity system is therefore based on agricultural activities (60%) with an average of 3 activities and a pluriactivity intensity of 2.76. Agriculture has an important place with an average time spent of 77% and a contribution of this activity to the overall income of the producers amounting to 72.5%. Pisciculture in fish ponds are practiced by 4.6% of farmers. Farmers in this type are men (80%), aged 42 years on average, educated to the level of primary education (50%), trained in rice (60%) and having large experiences in rice (6 years) and vegetable production (12 years). The size of their households is the highest (8.9 members).

4.2.3.9.4. PU4 Dynamic farmers with important productive resources and low investment capacity

This type consists of 24% of the sample. These production units have dynamic productive resources and low investment capacity. The farms are located in all agro-ecological zones as type 3. They are also in a dynamic of expansion of cultivated areas but due their low investment capacity, only inherited or borrowed lands are cultivated (2 430 m²). Also they do not have specialized equipment. Family labor is 3.1 agricultural active people and 75% of farmers do not use paid labour. The level of intensification is lower than type 3. 75%, 37.5% and 12.5% of farmers use fertilizer, herbicide and pesticide respectively. Agriculture remains important, with an average time spent by farmers (68%). It contributes to the overall income of 64%. The number of activities is an average of 2.81 and pluriactivity intensity is 2.33. This type consists of men (56%), uneducated (56%), somewhat trained in rice farming and vegetable production

(50%). Their rice and vegetable experience is relatively low. They are 43 years old on average with 6.7 members as household size.

4.2.3.9.5. PU5 Dynamic farmers with low productive resources and average investment capacity

These production units represent 12% of the sample and concern women in majority (88%), not educated (75%), somewhat trained in the rice cropping (75%) with important rice-growing experiences (4.5 years) and vegetable (12.5 years). Although they have farms in all agroecological zones, their available and cultivated areas are lower than those of types 3 and 4. They are also in a dynamic of expansion and intensification. Their investment capacity is lower than that of type 3 farmers, the areas on land inherited or borrowed (1400 m²) and land acquired or leased (2 330 m²) are lower. The undeveloped lowland areas are on average 3000 m². With no motor pumps or water hoses, they borrow or lease such equipments (63%). Respectively 100% and 63% of farmers use fertilizer and pesticides. Their system of activity is based on agriculture and trade (75%). The number of activities is 3.88 on average with a pluriactivity intensity of 3.27. The average time spent on agriculture is 64% and this activity contributes to the overall income of 64%. The average size of households is 5.8 with 2.4 agricultural active people. Their average age is 43 years.

4.2.3.9.6. FS1 Rice - maize system

This farming system concerns 30% of the surveyed sample. The rice variety IR 841 cultivated on the developed lowland is followed in dry season by maize (95%) in a rotating system (100%). Fertilizers are the only chemical inputs used by 65% of farmers on rice and 88% on maize. These two crops share less than 25% of the working time of the producers. The contribution of rice to farm income is between 25-50% and that of maize is less than 25%. Sown areas are extremely low 260 m². The average yield of rice is 0.99 ton ha^{-1}.

4.2.3.9.7. FS2 Dominantly rice system

This system concerns 15% of the surveyed sample. Rice is grown primarily on the undeveloped lowlands (60%) with the NERICA variety (70%). The rice fields are fertilized (60%) and 50% of farmers use herbicides mainly on no-tilled fields. These rice field husbandries take 25-50% of the working time of farmers (80%) and contribute to 50-75% of agricultural income (40%). The average cultivated area is 2720 m^2. The average rice yield is 1.18 ton ha^{-1}. With the exception of few pepper, eggplants and tomatoes on the hydromorphic fringes no other vegetables are cultivated in the valley bottom.

4.2.3.9.8. FS3 Semi-intensive system rice – vegetable system

This system concerns 12 of the surveyed sample. Vegetable crops grown after rice are the jute mallow installed in the developed lowland (63% of farmers), okra (50%) and pepper (75%). Pepper and okra are grown in the undeveloped lowlands. Two types of rice are grown: Beris 21 (50%) and IR 841 (75%). Only 38% of farmers use fertilizers on rice. On vegetables, 100% of farmers use fertilizers and 52% use pesticides. These farmers are in an intensive logic for vegetable production. 100% of the farmers practice the rotation rice - vegetable system on developed lowland and 50% on undeveloped lowlands. The average cultivated area for rice is 371 m^2 in developed lowland and 600 m^2 in the undeveloped lowlands. The average area of vegetable crops is 340 m^2 in developed lowland and 1 460 m^2 in undeveloped lowlands. The yield of rice is low (0.44 ton ha^{-1}).

4.2.3.9.9. FS4 Intensive system rice – vegetable system

This culture system represents 20% of the surveyed sample. In the developed lowland, 92% of farmers cultivate rice and the jute mallow in a rotation system (100%). Pepper (92% of farmers) and okra (100%) are grown in developed lowland in a relay cropping system on the same plots.

The most widely grown rice variety is Beris 21. 92% of farmers use fertilizers on rice. 100% of farmers use fertilizer and pesticide on vegetable crops. The average area for rice fields is 283 m^2 landscaped perimeter and 1 580 m^2 for both agro-ecological zones. The average vegetable area is 280 m^2 in the developed lowland and 7600 m^2 in the undeveloped lowlands. Farmers spend between 50-75% of working time in the rice fields for a contribution to farm income between 25-50%. Vegetable crops occupy 25-50% of the working time for a contribution to farm income between 50-75%. The yield of rice is low (0.37 ton ha^{-1}).

4.2.3.9.10. FS5 Rice – diversified vegetable crops system

This system is represented by 23% of the surveyed sample of farmers. The crops are mainly cultivated in the undeveloped lowlands. The rice variety grown is the NERICA (93% of farmers). 67% of farmers practice rice - vegetable systems on different fields. At least three vegetable species are cultivated by each farmer. These species are the okra (64% of farmers), tomato (87%), and the jute mallow (73%), eggplant (93%). The rice fields are fertilized (73% of farmers) and 60% use herbicides. The uses of these inputs reflect the intensification processes of rice production systems. No chemical input is used in vegetable production. The average cultivated area in rice is 4000 m^2. The average rice yield is somewhat low (1.09 ton ha^{-1}). Cultivated vegetable crops area is very low (92 m^2).

4.2.3.10. Determinants of weed management practices

An attempt was made to identify factors which best differentiate weed management practices. Variables describing the production units and farming systems were used in an indirect PCA gradient analysis in order to identify the most significant contribution to the weed management practices (Figure 35). The principal component analysis (PCA) revealed links among the five productions units and farming systems. Axes 1 and 2 explained 54% of this representation where axis 1 may be qualified as an 'herbicide axis'. Herbicide uses linked to WM2 and WM3 were grouped on the right side of the diagram: these weed management methods were related to farming systems 2 (FS2), farming systems 4 (FS4) and farming systems 5 (FS5). FS2 is mainly characterized by dominantly rice system on no-tilled field, FS4 is linked to intensive system rice – vegetable system, and FS5 is related to rice – diversified vegetable crops system. The herbicide uses were related to the following production units (PU2, PU3 and PU4). PU2 is characterized by farmers cultivating in undeveloped lowlands, PU3 is related to farmers with significant resources and strong capacity for investment and PU5 is linked to dynamic farmers with important productive resources and low investment capacity. For the second axis 2, intensification of rice-vegetable systems was the main leading criteria. In the upper half of the diagram, intensive rice-vegetables systems (rice-jute mallow and rice-okra) are related to FS3 and FS4. FS3 constitutes the semi-intensive system rice – vegetable system while FS4 represents the intensive system rice – vegetable system. This semi-intensive and intensive rice-vegetable systems comprise the production unit PU3 (mainly male farmers with significant resources and strong capacity for investment) and PU5 (mainly women farmers with low productive resources and average investment capacity).

The weed management practices being largely influenced by the production units will determine the timing of the weeding operations.

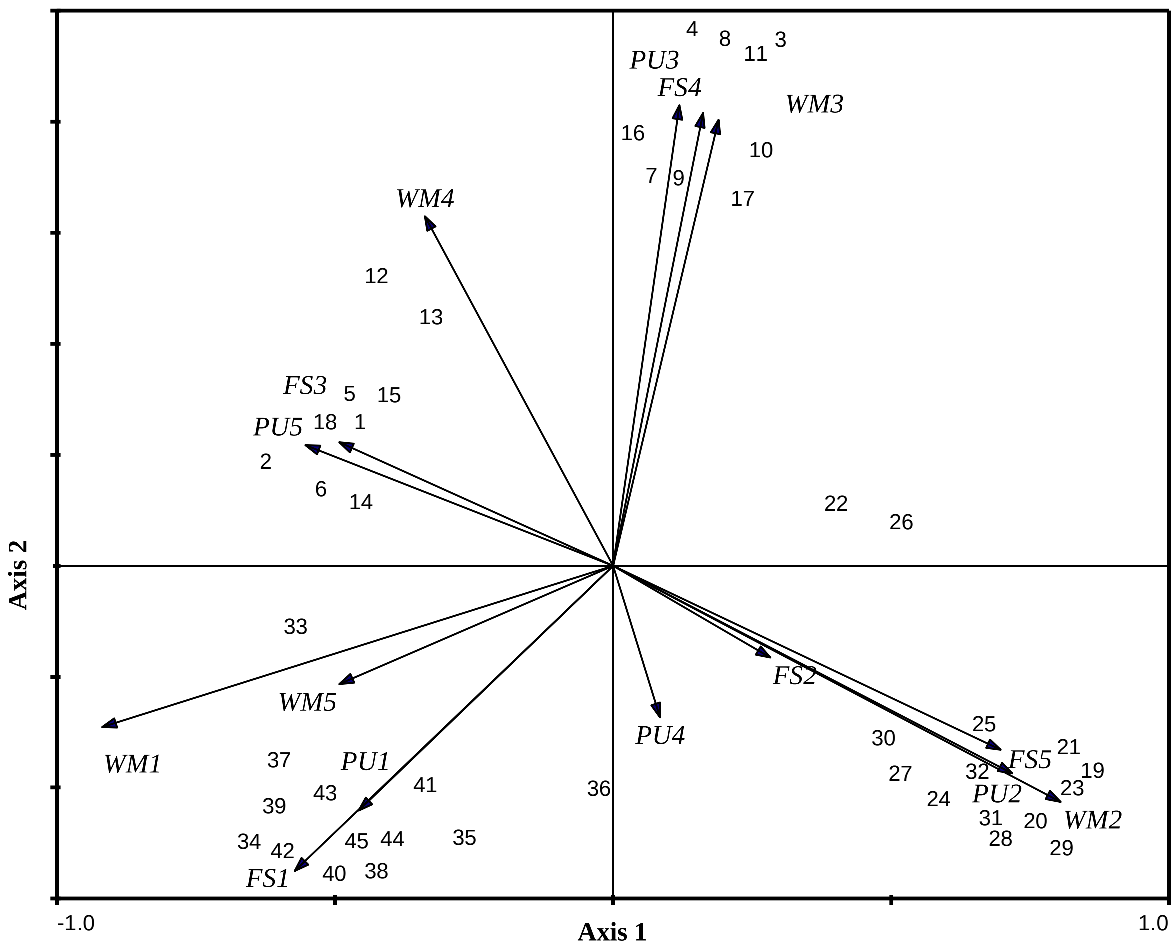


Figure 35. Graphic representation of the principal component analysis. The individual (45 surveyed farmers) are represented by numbers, and the production units (PU's), farming systems (FS's) and weed management method s (WM's) are noted.

4.2.3.11. Crop yields losses under different weed control practices and production units

Rice yields were lowest in WM1 (section 4.2.3.1.) with a mean of 1271 kg ha^{-1} and in PU1 with a mean of 731 kg ha^{-1} (section 4.2.3.6.). Yields were highest in WM3 (mean of 2235) and PU3 (mean of 2277 kg ha^{-1}) (Figures 36 A and 36 B).

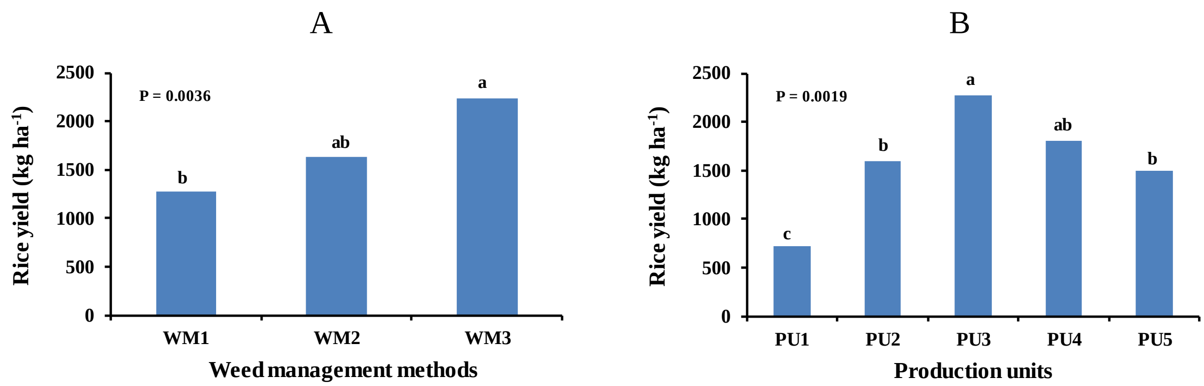


Figure 36. Average rice yields obtained by farmers under different weed control practices (A) and production units (B).

4.2.3.12. Labor allocations for weeding fields by different production units

There labour for hand weeding was essentially family labour for the three lowland sites, with 3 to 4 family members in general helping. Children came often after school for weeding operations, but spent less time on the plots as they arrived later and often left earlier for attending school. Some farmers hired labour for weeding. Hired labour constituted 25% of the total labour for hand weeding at Agbedranfo in directed seeded rice and vegetables systems (jute mallow and okra), while no to few hired labour was used at Houinga and Vovokame for weeding respectively rice and maize. The rates for weeding rice, jute mallow and okra were respectively 1500, 3500 and 700 CFA/*kanti* ($400m^2$). Jute mallow weeding was the most costly, leading farmers to resort to mutual helping groups and to cultivate small sized farms.

Concerning rice cultivation, farmers in PU1 and PU5 weeding with hand hoeing and pulling spent most time weeding their rice fields with 1.04 and 1.02 days ha^{-1} respectively. Whereas farmers in PU2, PU3 and PU4 using herbicides spent less time weeding their rice fields with respectively 0.78, 0.52 and 0.35 days ha^{-1} (Figure 37). Compared to farmers in PU5, farmers in PU1 delayed more the first weeding operations done incorrectly with above parts of weeds cut by hired occasional labour (Figure 38).

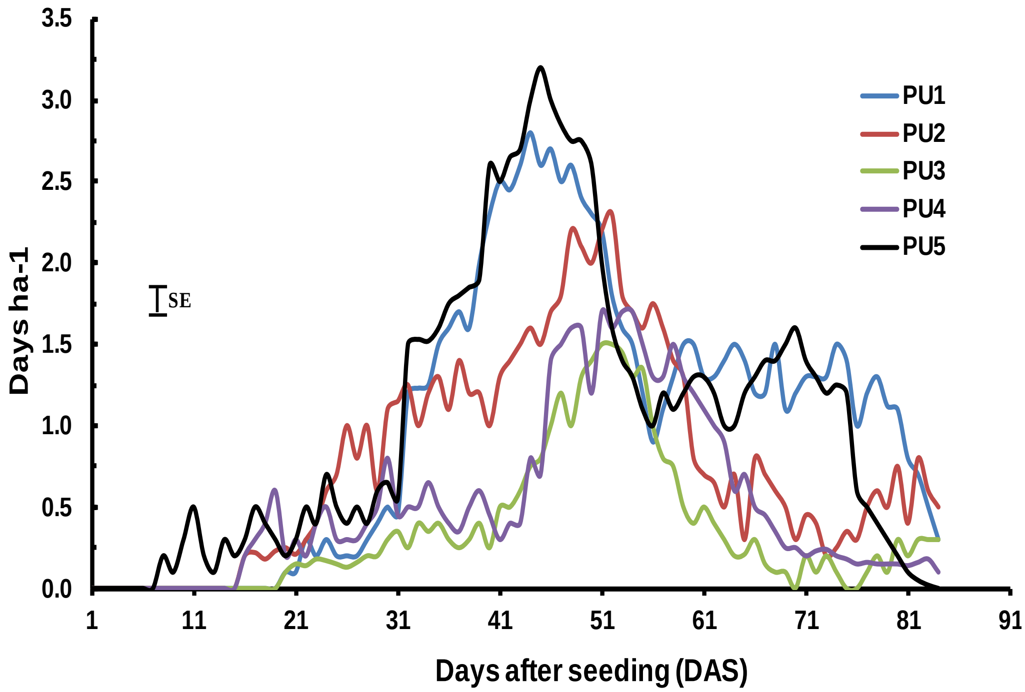


Figure 37. Average time spent weeding rice in five production units in inland valleys of Benin 2010-2011.

Figure 38. Inefficient rice weeding performed in PU1by hired laborers at Vovokame.

4.2.3.13. Decisions about weeding rice

In order to alleviate the weeds problems in these agroecologies through the analysis of the diversity of rice-vegetables production units, actions models closely related to the production units were found. The different production units combined the contents of farmers objectives and strategies, labour availability and four decision rules: (1) rules defining the number of rice/vegetables weeding sessions and their activation rules; (2) arbitration rules for setting priorities between crops (3) rules determining the modes of weeding to be used for the crops; and (4) arbitration rules for deciding priorities among crops for the first weeding operations (Table 12). In the weeding activation rules, June to July for rice is the earliest first weeding dates practiced with hoeing or selective herbicide. In addition to total herbicide glyphosate used for land preparation mainly in PU2, 2,4-D selective herbicide against broad-leaved species was used mainly in PU3.

Table 12. Content of decision rules for rice first weeding on production units (PU) during the rainy season.

Production unit (PU)	Rice farmers objectives and strategies	Labour availability on PU	Content of decision rules		
			Activation of rice first weeding	Arbitration between crops for first weeding	Weeding modes
PU3	Self-sufficiency in staple foods (rice) through higher yield through extension of territories inherited, acquired or leased with improved irrigation tools (motor pump and PVC tubes), increase income (sale of vegetables + fish), financing school fees	Family and/or salaried labour force	Start around mid- June after weeding of maize fields	When weeds cover over 30% of ground area, rice weeding takes priority	Hand hoeing/ selective herbicide
PU4	Self-sufficiency + sales of staple foods with higher yield through intensification but renting improved irrigation tools (motor pump and PVC tubes)	Medium sized family/salaried labour force	Start around early July after weeding of maize fields	When weeds cover over 30% of ground area, rice weeding takes priority	Hand hoeing
PU2	Self-sufficiency + sales of staple foods through higher yield with intensification and extensification	Large sized family/family labour force	Start around early July after weeding of maize fields	When weeds cover over 30% of ground area, rice weeding takes priorities	Total herbicide for land preparation + Hand hoeing
PU5	Self-sufficiency in staple foods (rice), diversification of incomes (transformations of agricultural products)	Medium to small sized family labour force	Start around early July after weeding of maize fields	When weeds cover over 30% of ground area, rice weeding takes priority	Hand pulling + hand hoeing
PU1	Self-sufficiency in staple foods, but because of low productive resources and low labour forces, diversification of incomes (trade, casual labour)	Small sized family labour force + low wage hired labour	Start around mid-July after weeding of maize fields	Trade + casual labour take priority over first weeding	Hand pulling + hand hoeing

4.2.4. Discussion

In the lowlands of study areas with dominant grass and sedge vegetation, at the on start of the rainy or dry season, clearing the fields by slashing and burning the weed regrowth were performed on relatively non-significant biomass with increasing difficulties. Because grasses and sedges with rooting rhizomes and stolons resist slashing, subsequent drying out and burning. Thus clearing may leave the soil more or less bear with small bits of these plants litter the ground with the immediate occurrence of vegetative spread by layering and root sprouting amid patchy ashes. The deposit of the ashes forms irregular patterns over the field but ashes are not re-distributed over the field (Akobundu, 1987). Thus, incomplete burning was quite common. It was mainly due to the patchy distribution of dry vegetation over the field. A poor, overall burning was frequent, and because of the moist condition observed in the inland valleys, re-burning was not considered worth the trouble (De Rouw, 1991).

Land preparation practices varied according to cropping systems and contributed in controlling weeds in rice, vegetable crops and maize. For most farmers surveyed, the land preparation (tillage and harrowing or breaking soil clods into smaller particles) was carried out mainly for burying and incorporating weed residues, therefore easing the following weeding sessions. Land preparation did not comprise any puddling. Farmers at Agbedranfo and Vovokame practicing rice-vegetables (rice-jute mallow or rice-okra) and rice-maize systems tilled and harrowed manually once their lands before planting rice, jute mallow, okra and maize. The tilling and harrowing with hoe were generally done few days after the fields were thoroughly flushed with rainfall and/or irrigation water from the artesian well**.** Overall, land tilling did not clear nor suppress the existing weeds, enabling those weeds to rapidly regrow before rice seeding. At Agbedranfo and Vovokame, the average time spent by farmers in preparing their fields for establishing rainy season rice was 115 labors/hours/ha. While for off-season crops, 95 labors/hours/ha was needed for field preparation, probably due to less weed cover resulting from rice cultivation and resulting weed control measures and the onset of the dry season implying the cessation or slowing of vegetative growth. Those labors figures for land preparation lie within the ranges given by Stessens (2002). At Houinga, minimum tillage (the rice crop was grown most of the times on herbicided slashed vegetation with superficial scrapping of top soil with hoe) was practiced by the 14 farmers surveyed. As a result, the average time spent on land preparation was 15 labors/hours/ha or an 87% saving in time required for land preparation compared to the farmers' practices at Agbedranfo and Vovokame. Application of glyphosate before planting rice can reduce labor input by 30-60% (Roder et al., 2001).

Planting and spacing methods are very important in determining the outcomes of weed–crop interactions and preventive management measures. A vigorous rice crop with a closed canopy denies weeds space and light (Rodenburg and Johnson, 2009). On the sites, row or line planting was the common planting methods for the cultivated crops, except for jute mallow which was broadcast by the farmers without any consideration concerning the optimal seed density. That resulted in high plant population with limited space in between, making weeding operations very difficult. Also for most row seeding cases, most farmers tended to overplant, and only few thinned later the plants. Transplanting was usually done with 21- to 30-day-old rice seedlings, although often much older, and these were planted in rows. Furthermore, it provided the rice crop with a competitive (size) advantage over weeds, and the soil could be flooded immediately after transplanting which suppressed the emergence of the majority of the potential weed species. Transplanting in rows facilitated the use of labor and time-saving weeding equipment such as a hoe. Moreover, grasses that have similar appearance as rice, especially in the early stages, are easier to recognize if they occur outside the planting pattern (Rodenburg and Johnson, 2009).

Hand weeding was intensively used for weed control at Agbedranfo and Vovokame, and extensively used at Houinga. Most farmers in the three survey areas recognized that weeds competed with their crops. In most of west African inland valleys, farmers are generally aware that when weeds compete with rice, vegetables, maize and other crop, growths are stunted, yields are low, and the quality of the harvested product are poor (Akobundu, 1987). Weeding was done twice for most crops grown, although more weedings were done on the jute mallow at every 2 weeks before harvest consisting of cutting leaves, thus 2–8 weeding sessions might take place. For the broadcast seeded jute mallow system, it was difficult to enter and to weed the fields without damaging the plants. Hand pulling was the only weed control method applicable, because the spatial arrangement made hoe weeding difficult, and the farmers had little or no knowledge of chemical weed control on vegetables (Hamma et al., 2012). Hand pulling was also applied on the other crops for most weeds (e.g. *Ageratum conyzoides*, *Phyllantus amarus*) arisen from seeds that had such limited root systems. Perennial weeds mainly grasses and sedges (e.g. *Imperata cylindrica*, *Cyperus rotundus*) with rhizomes which could not be pulled out were partly uprooted with hoes and cutlass. Thus, the manual weeding sessions did not control systematically most weeds, and in some cases weeding and hoeing provoked growth of new seedlings of *Commelina benghalensis* and *Digitatia horizontalis* (Le Bourgeois and Marnotte, 2002).

Herbicide was solely used on rice; no herbicide was applied on vegetables and maize. The non-availability of herbicide, lack of training on herbicide use and lack of credit were the main constraints (Rodenburg and Johnson, 2009). Farmers' objectives for herbicide uses were weed pressure reduction for crop yields increase and costs reduction of labour and weeding. Herbicides were purchased in the market. Surprisingly, there was more herbicide application in transplanted rice than direct seeded rice (67% versus 30%). Because the major problem associated with direct seeding culture is the incessant competition with weeds. In opposition to transplanted rice, direct seeded rice does not have a two-to three-week head start over weeds. But for the surveyed plots, more total herbicide glyphosate was sprayed at Houinga with undeveloped lowland which had larger transplanted fields (area>3500 m^2) with more problem perennial grass weeds such as *Imperata cylindrica*. Also at Houinga labour was not hired for hand weeding; and that fact rendered herbicides uses somewhat economical. Total systemic herbicide glyphosate and phenoxy selective herbicide 2,4-D were used by farmers using herbicide and who transplanted or direct seeded their rice. Overall, herbicides uses gave good results on rice yields, particularly in minimum tillage systems at Houinga. However, almost everywhere these chemicals were too expensive for farmers leading to reduction in the rate of applied herbicide that would reduce the herbicide cost but increase the time spent in weeding the dry-seeded rice field because of reduced weed control (Rao et al., 2007).

There were no significant differences between the different weed control practices along the heterogeneous catena positions. There was no attempt to introduce any improved water management technology (e.g. bunding, drains, terraces, ridges) at each catena position for smothering weeds. This implied the absence on the study sites of a spatially more stratified targeting of technical options, considering not only soil type and climate as in the site-specific crop management of Asia (Aulakh and Grant, 2008). The non validation of the hypothesis of no influences of different cropping practices on weed flora along the catena will be the major link between the study conducted in Benin and the one conducted *ex ante* in Cote d'Ivoire (chapter 5).

Smallholder agricultural systems in West African inland valleys are diverse and spatially heterogeneous farms distributed along the catena. A functional typology can help in categorizing the diversity of production units based on of livelihood strategies, and in analyzing the influence of such diversity on status of abiotic factors and spatial variability (Bidogeza et al., 2009; Tittonell et al., 2010a). In the present study, the typology identified five different production units in these inland valleys based mainly on land, labour, pluriactivity and financial resources all of which has an influence on agricultural productivity and weed management. Although some of the criteria represented drivers of social diversity (e.g. availability of land and labour), others were simply a consequence of differences between production units as induced by such drivers of diversity (e.g. timely weeding, use of inputs). Timely weed management was closely associated with labour availability. PU1 farmers (dominantly part time farmers on very small sized fields with casual employment) and PU5 farmers (dominantly women farmers with low productive resources and average investment capacity) had labour shortage early in the cropping season, leading to delayed first weeding affecting negatively rice yields. In West African inland valleys agroecologies, delayed first weeding is known to affect negatively most of the annual crops (Akobundu, 1987). PU2 farmers (dominantly large fields in undeveloped lowlands) delayed their first weeding due to the use of total herbicide in the minimum tillage systems. NGO (nongovernmental organization) through the multi stake holder platform (MSP) played crucial role in supplying those farmers with herbicides with good results on rice yields. PU3 farms relying mainly on agriculture-based livelihood strategy represented wealthier farmers owning relatively large farms, growing vegetable crops in rotation with rice who relied mostly on income generated by farming and sometimes by pisciculture. PU4 farms have similar income generation strategies but were less endowed in land and/or capital, and some family members might engage sporadically in off-farm activities to cover expenditure (e.g. school and health fees). PU3 and PU4 farmers (better endowed farmers) had access to herbicides and labour (family or hired) and the first weeding was not delayed, leading to better rice yields. Those farmers who exhibited more agriculture-based livelihood strategy are more likely to implement and eventually adopt proposed technologies for agricultural intensification (Tittonell et al., 2010b).

In addition to biotic and abiotic constraints, resource limitation may often induce a shift in livelihood strategies (Thornton et al., 2007), which manifested as a shift towards a higher dependence on off-farm income. This might have an effect on decision-making, farming practices and certainly on household priorities for investing cash and labour resources (Crowley and Carter, 2000). For rice cropping calendar, the first two weedings occurred during the months of June and July, and at that time, labour pressure was very high. Land preparation and planting of other crops, and weeding rice competed for the farmer's limited labour, thus the competitive effect of weeds was greatest at this time, early in the rice crop's life. In this situation, arbitration rules between weeding rice fields and the cultivation of other crops were in favor of staple food such as maize, leading to the rice weeding inefficiency due to delayed weeding. In practice, most farmers were prepared to do the first weeding within the 28 DAS, and was little prepared to do the second extra weeding at around 56 DAS which coincided with the harvest of maize. From these observations, it could be deducted that decisions about hand weeding was made around 2 months after seeding. An estimated weed cover of 16-30% might be a motive to start the first weeding, provided the rice plants were in good condition. And for the second and third weeding, no matter the weed cover, corn harvest determined the weeding sessions.

For improved weed control practices such as the uses of herbicide in production unit with more literate and trained farmers, the decision making about the use chemicals were largely influenced by the interactions with extension agents and training sessions. This allowed farmers to exchange views and identify expertise and knowledge gaps in order to better target problem weeds, and develop improved approaches and control options (Rodenburg and Johnson, 2009). Such interactions might improve farmers'decision making and consequently enhance weed management, as this is highly dependent on exposure to technologies and access to information (Becker et al., 2003; Escalada and Heong, 2004; Haefele et al., 2002; Heong et al., 1998; Heong et al., 2002; Rao et al., 2007).

4.2.5. Conclusion

Differences in weed control practices for crops within and across sites were noted. Across the three sites, hand weeding remained the major means to control weeds. Herbicides uses were limited because of the expense and limited cash. No significant differences were found between the different weed control practices along the heterogeneous catena positions. Within a site, the primary determinants of the weed control method used were the financial and labour resources of the farmers. The time required for hand weeding was much greater and yields lower in dry-seeded rice for poorer farmers (mainly women and part time farmers with casual employment), and herbicides could play a major role in weed control. Our results indicated that for increasing rice yield, the field must be hand weeded at least twice with an earlier hand weeding or a total herbicide can precede and a preemergence herbicide treatment must be followed by a supplemental hand weeding about five weeks after crop sowing to control the second generation of weed growth. The staple food crop maize harvesting took priority over weeding operations. For rice and other crops cultivated in inland valleys, the weed control measures that are developed for introduction into the existing cropping system should be compatible with the farmers' resources. Emphasis should be placed on systems that require a minimum cash input and a moderate level of labour. The labour requirements should not exceed that which the farmers can afford.

4.3. Farmers' perceptions on weeds in inland valley of the Mono Couffo regions of Benin

4.3.1. Introduction

For rain-fed lowland rice production in sub-Saharan Africa (SSA), weeds generally are the greatest yield-limiting factors. In these ecosystems, uncontrolled weed growth is reported to cause yield losses in the range of 28 to 98% in West Africa (Akobundu, 1980; Becker and Johnson, 2001; Johnson et al., 2004). To reduce weed pressure, most upland rice farmers rely largely on land preparation, pre and post-harvest fires and hand or hoe weeding along the heterogeneous catena of the inland valleys. Labor intensive hand weeding is often preferred by farmers because the use of herbicides is associated with relatively high costs and market failures, while low literacy rates among farmers in SSA further limit herbicide use (Rodenburg and Johnson, 2009). But all weeds are not noxious; some weeds found in rice based systems have one or more direct benefits for African farmers in terms of domestic and medicinal uses (Akobundu, 1987; Burkill, 2004; Rodenburg and Johnson, 2009). As the uses of weeds as auxiliary is common in the study areas, and as farmers have to balance the value of weeds against their damaging effects on crop growth, farmers' perceptions of the importance and use of weeds were assessed along the heterogeneous catena.

4.3.2. Methods

According to the method developed by Weber et al. (1995), farmers' perceptions on importance and weed management were assessed. 45 farmers in the three villages were asked to bring those weeds from their fields which they consider to be important, and the weed interviews with farmers took place in the fields designated for sampling (Figure 39).

Figure 39. Farmers identifying important weeds (Vovokame, Benin).

And respondent farmers were encouraged to give independent answers without the influence of other village members. As Agbedranfo and Vovokame formed one MSP (because of their proximity), the two villages were considered as one, and Houinga site was single sided. All weeds which farmers perceived as their most important problem were encountered in most fields during field monitoring. For farmers' perceptions, main focal points were the following: (1) importance of weeds, (2) efficient weed control methods, and (3) usefulness of weeds.

Descriptive statistics were generated and the data obtained from the survey was converted into percentages and mean values.

4.3.3. Results

4.3.3.1. Importance of weeds according to farmers

Farmers identified twenty seven weeds species (important to them) scattered along the heterogeneous catena from the valley crest through the hydromorphic fringe to the valley bottom

(Table 13). The species were brought and identified by the three village farmers. Local names given by farmers in one village were cross-checked in other villages. In most cases, farmers differentiated weeds only up to the level of genera. Grasses and sedges were best differentiated as they are among the most commonly occurring weeds in intensified lowland-rice vegetables farming systems. Most names were descriptive (for example) *Awlivi*, a milky sap species (*Euphorbia heterophylla*).

Some of the species (e.g. *Ageratum conyzoides*, *Digitaria horizontalis*, *Paspalum scrobiculatum*, *Commelina benghalensis*) identified as important by farmers were also listed as dominant species by the survey conducted in the quadrat installed in the farmers' fields (see section 4.1.3.1).

Table 13. Major weeds at Agbedranfo, Vovokame and Houinga 2010.

Adja/Saxwè name	Family name	Genus	Species	Abbreviations
Bomigbé	Amaranthaceae	*Alternanthera*	*sessilis*	*Alte ses*
Etogbé	Asteraceae	*Ageratum*	*conyzoides*	*Ager con*
Etogbé	"	*Eclipta*	*prostrata*	*Ecli pro*
Toflé	"	*Synedrella*	*nodiflora*	*Syne nod*
Toflé	"	*Vernonia*	*cinerea*	*Vern cin*
Botamakouimakoui	Commelinaceae	*Commelina*	*benghalensis*	*Comm ben*
Gbélémiadoui	Convolvulaceae	*Ipomoea*	*aquatica*	*Ipom aqu*
Fiokoui	Cyperaceae	*Cyperus*	*difformis*	*Cype dif*
Fiokoui	"	*Cyperus*	*distans*	*Cype dis*
Fiokoui	"	*Cyperus*	*tuberosus*	*Cype tub*
Fiokoui	"	*Fimbristylis*	*littoralis*	*Fimb lit*
Awlivi	Euphorbiaceae	*Euphorbia*	*heterophylla*	*Euph het*
Etchigbé	Logoniaceae	*Spigelia*	*anthelmia*	*Spig ant*
Etchigbé	Onagraceae	*Ludwigia*	*decurrens*	*Ludw dec*
Ekoui	Poaceae	*Brachiaria*	spp	*Brac* spp
Clobou	"	*Digitaria*	*horizontalis*	*Digi hor*
Ekoui	"	*Echinochloa*	*colona*	*Echi col*
Ekoui asou	"	*Eleusine*	*indica*	*Eleu ind*
Ebé	"	*Imperata*	*cylindrica*	*Impe cyl*
Tchiantchikoui	"	*Leersia*	*hexandra*	*Leer hex*
Okpui	"	*Leptochloa*	*caerulescens*	*Lept cae*
Okpui	"	*Panicum*	*maximum*	*Pani max*
Zakpatakoui	"	*Paspalum*	*scrobiculatum*	*Pasp scr*
Adjigba	"	*Rottboellia*	*cochinchinensis*	*Rott coc*
Gburui	Portulacaceae	*Talinum*	*triangulare*	*Tali tri*
Gbantou	Solanaceae	*Physalis*	*angulata*	*Phys ang*
Crincroui	Tiliaceae	*Corchorus*	*aestuans*	*Corc aes*

Twelve species were most frequently mentioned by farmers as being important and almost all of them were seen as increasing in incidence (Figure 40). *Imperata cylindrica*, *Commelina benghalensis, Euphorbia heterophylla, Ludwigia deccurens, Digitaria horizontalis, Ageratum conyzoides, Brachiaria* spp., *Paspalum scrobiculatum*, *Cyperus distans, Echinochloa colona, Rottboellia cochinchinensis* and *Alternanthera sessilis* was mentioned by 42, 38, 36, 35, 34, 33, 29, 27, 23, 20, 13 and 12% respectively of the farmers as weeds whose importance was increasing

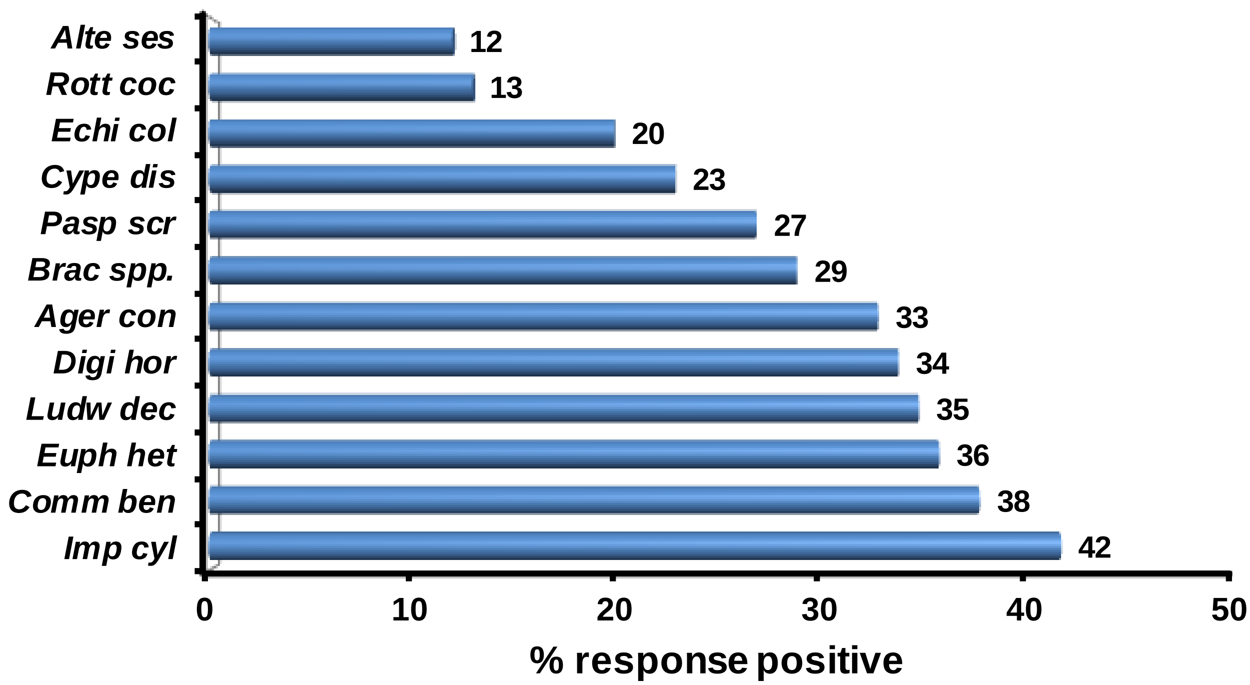


Figure 40. Most important weeds according to farmers' perceptions in the study villages of Agbedranfo, Vovokame, and Houinga 2010-2011. Abbreviated species names are listed in Table 13.

As reasons for their importance, *Imperata cylindrica*, *Commelina benghalensis*, *Rottboellia cochinchinensis*, *Cyperus distans*, *Digitaria horizontalis*, *Euphorbia heterophylla*, *Paspalum scrobiculatum* were observed by farmers to reestablish easily after weeding, to cause injury to the skin, and to produce many seeds (Figure 41). For farmers the importance of these weeds was noted if weeding was not done carefully and repeated three to four times or if adequate soil moisture after weeding allowed the weeds to establish themselves again.

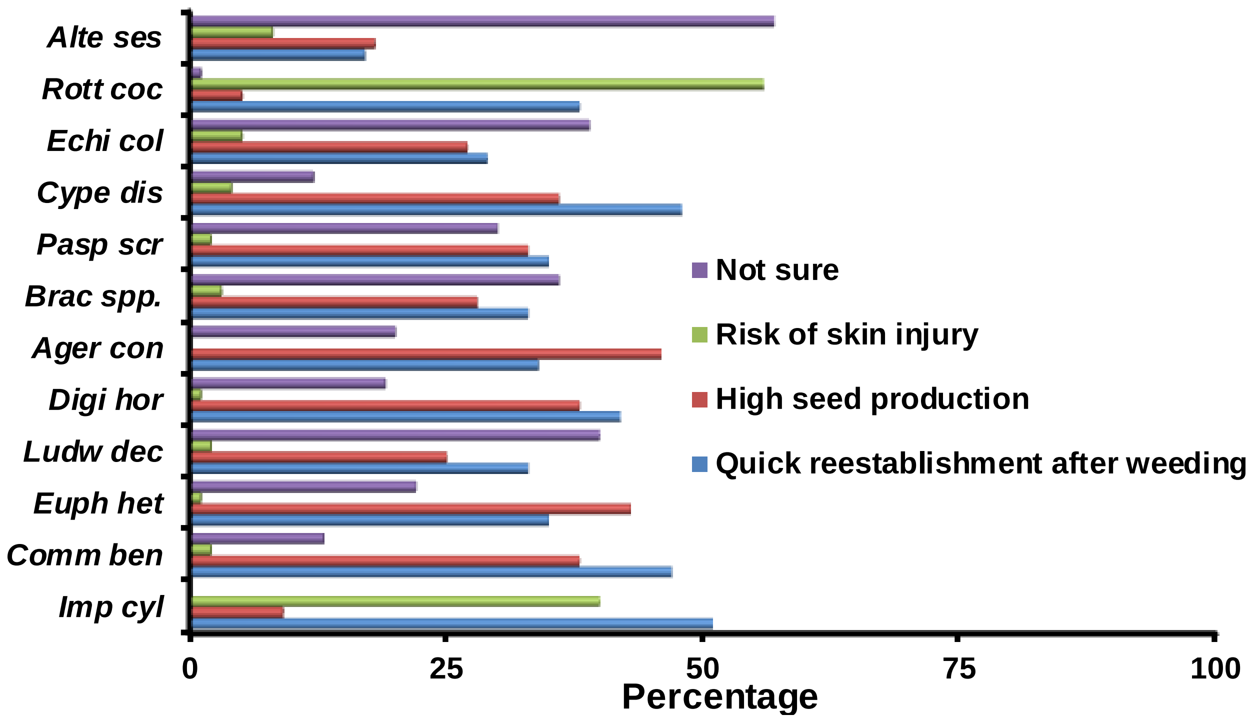


Figure 41. Percentage of farmers indicating reasons for increasing importance of weed species in the study villages of Agbedranfo, Vovokame, and Houinga 2010-2011. Abbreviated species names are listed in Table 13.

4.3.3.2. Efficient weed control methods according to farmers

In open-ended interviews with farmers on efficient methods for weed control, five methods were identified for dominant weed species. For efficient weed control methods, weeding with removal of weeds, weeding before seed shed, herbicide use, and burning the residues were mentioned as efficient for most weeds (Figure 42). Plowing and incorporation of residues was applied to *Rottboellia cochinchinensis*, *Alternanthera sessilis*, *Ageratum conyzoides*, *Euphorbia heterophylla* and *Ludwigia deccurens*.

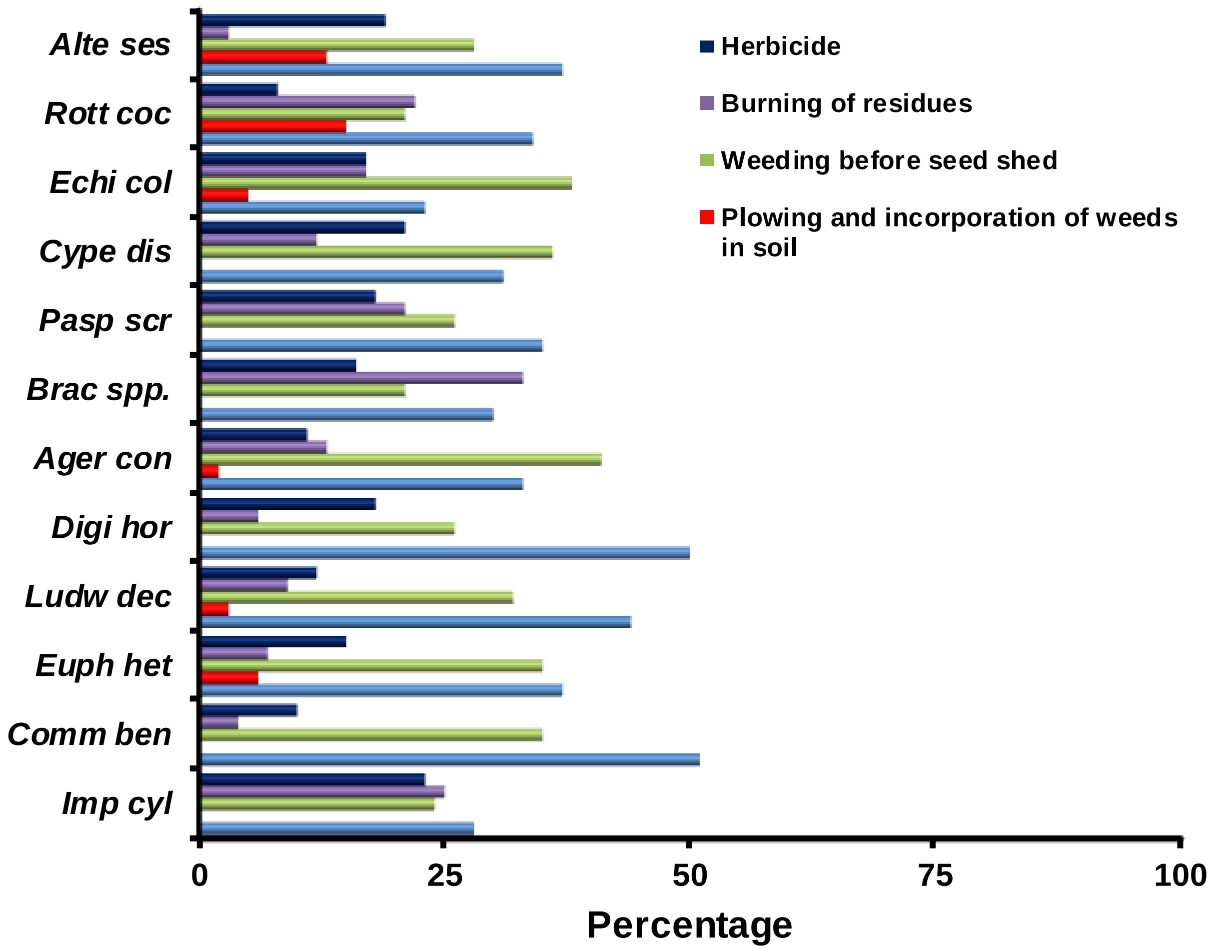


Figure 42. Most efficient weed control for some major weeds as indicated by farmers in the study villages of Agbedranfo, Vovokame, and Houinga 2010-2011. Abbreviated species names are listed in Table 13

4.3.3.3. Usefulness of weeds according to farmers

Nine species were frequently mentioned by farmers as useful plants (Figure 43). The major uses of most of these plants were fodder to cut and carry during the rainy season for some goats tied to ropes, to prevent them from entering crop field, and vegetables. The fodder concerned mainly grasses such as *Paspalum scrobiculatum*, *Panicum maximum*, and *Eleusine indica*. Leafy vegetables concerned species collected in the wild such as *Corchorus aestuans*, *Talinum* *triangulare*, *Vernonia cinerea*, and *Althernanthera sessilis*. And as dual plant (in addition to be consumed), *Althernanthera sessilis* was mentioned as medicine for some ailments (Figure 44). *Eclipta prostrata* was solely mentioned for medicine. *Imperata cylindrica* and *Panicum maximum* were mentioned as roofing material for construction (Figure 45).

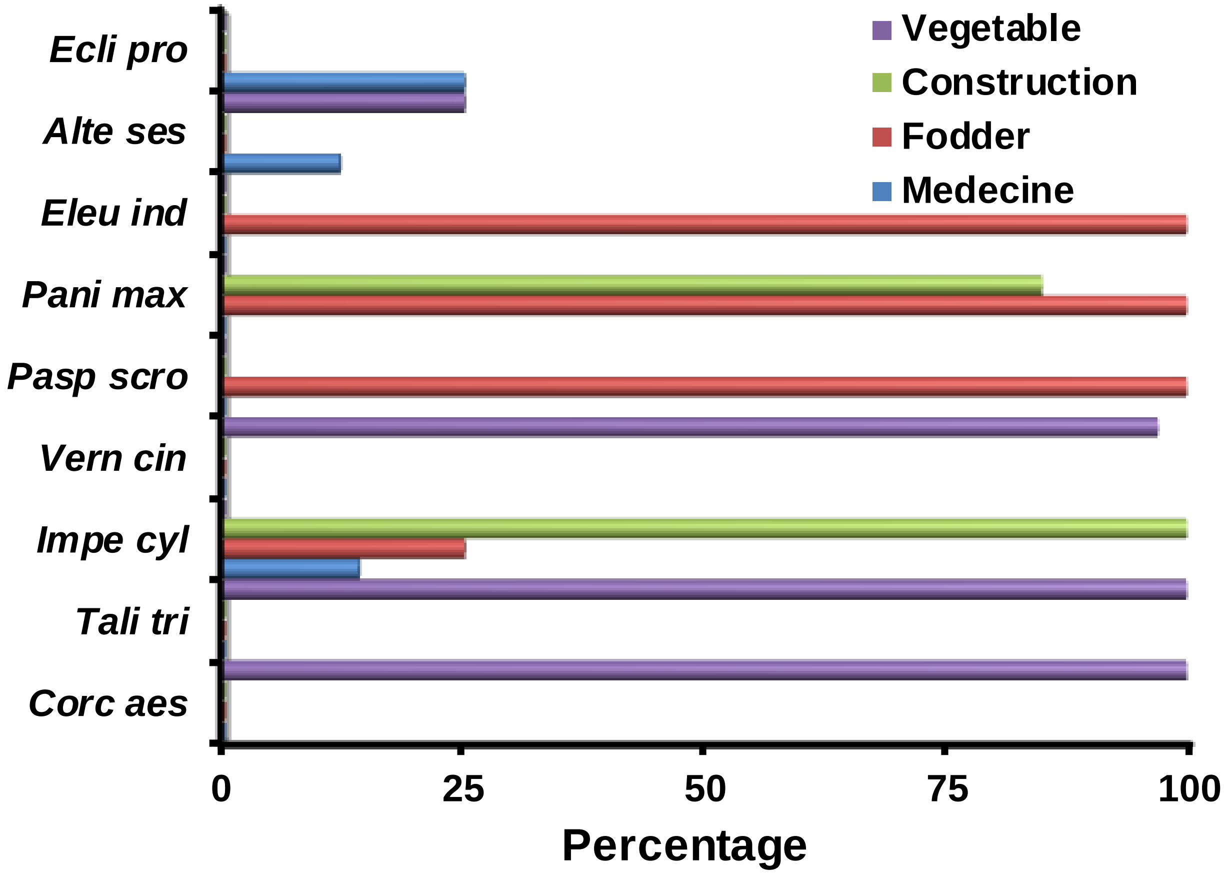


Figure 43. Weeds recognized as useful by farmers of study villages of Agbedranfo, Vovokame, and Houinga 2010. Abbreviated species names are listed in Table 13.

Figure 44. Harvesting *Alternanthera sessilis* leaves for domestic uses.

Figure 45. Thatching of *Imperata cylindrica* straws for roofing material.

4.3.4. Discussion

The importance of weeds according to farmers was mostly related with the hand weeding method practiced by farmers. But surprisingly, *Rottboellia cochinchinensis* was listed as important weed problems by the farmers, because this weed hardy becomes a problem in small-scale farms where hand weeding is practiced. In fact, the species is known as a weed of large-scale farms, where weeding is intensive through machinery and/or herbicides uses, and its seeds are distributed by machinery and contaminated seeds (Weber et al., 1995). Regarding weed control practices, perennial grasses with rhizomes and stolons such as *Imperata cylindrica* and *Paspalum scrobiculatum*, and perennial rhizomatous sedge *Cyperus distans* are difficult to control by hand weeding, thus constituting a serious problem for small-scale farmers who depend on hoe weeding for all their weeding operations. Some grasses (*Rottboellia cochinchinensis*, *Echinochloa colona*, *Paspalum scrobiculatum* and *Brachiaria* spp.) and broadleaved (*Euphorbia heterophylla*, and *Ageratum conyzoides*) were listed as yield and quality reducing factors by farmers. A common characteristic to these weeds contributing to their detrimental effects on crop yields are their prolific seed production, and particularly for the broadleaved species (*Euphorbia heterophylla*, and *Ageratum conyzoides*), the seeds are dispersed explosively through dehiscent seed capsules, and may mix with crop grains (Rodenburg and Johnson, 2009). Moreover, during the rice cropping season, *Echinochloa colona* exhibits another problem weed characters as its close resemblance with rice (crop mimicry by weeds) at the early stages of growth which often causes confusion during hand weeding, and also it has a competitive and short life cycle (Rodenburg and Johnson, 2009). *Imperata cylindrica*, *Commelina benghalensis*, *Rottboellia cochinchinensis*, *Cyperus distans*, *Digitaria horizontalis*, *Euphorbia heterophylla*, *Paspalum scrobiculatum*, were observed by farmers to reestablish easily after weeding, to cause injury to the skin, and to produce many seeds, if weeding was not done carefully and repeated three to four times or if adequate soil moisture after weeding allowed the weeds to establish themselves again. Most of those weeds cited by farmers have been reported as troublesome weeds elsewhere in West Africa (Ahanchede and Gasquez, 1997; Feuillette et al., 1997; Weber et al., 1995). For example for some of those weeds such as, *Imperata cylindrica* is a perennial species that mainly multiplies vegetatively by extension of a vigorous rhizome system. As an alternative means of propagation, its seeds can also be dispersed widely by the wind. Fires, cutting and grazing induce regrowth and stimulate flowering. In addition, it can cause injury to the skin during weeding operations. For *Commelina benghalensis*, weeding is tedious; because this weed has a succulent stems and has ability to produce above and underground seeds, and has high vegetative propagation potential via layering or branch cutting. *Rottboellia cochinchinensis* causes serious problem, because it has irritating hairs on its stem which makes it difficult to control manually in small-scale farms. Also, *R. cochinchinensis* has plasticity for a renewed germination from the seeds in the soil. *Cyperus distans* is difficult to eradicate by manual weeding because of its underground rhizomes and tubers. *Digitaria horizontalis* is a problem weed for farmers, because of its rapid growth and its reestablishment through stolons. *Euphorbia heterophylla* is a very competitive weed, because it can rapidly form closed canopy, and has a life cycle of only 60 days from germination to seed setting, contributing to a rapid buildup of the population. Also, *E. heterophylla* breaks off at ground level when pulled and produces new shoots which may require additional weeding (Rodenburg and Johnson, 2009).

Weeding and removing residues concerned species such as *Imperata cylindrica*, *Commelina benghalensis*, *Digitaria horizontalis*, and *Cyperus distans* which can easily reestablish themselves in the field through their vegetative propagules, requiring to be removed from the field for complete control.

Whereas *Ageratum conyzoides* and Euphorbia *heterophylla* rely on profuse seeds production for their propagation. Thus, farmers considered weeding before seed shed to be more efficient for these species. However, most farmers did not have adequate resources to prevent weeds from flowering and seed shedding towards the later part of the season.

Most of farmers at Houinga and some at Agbedranfo used herbicides during the rainy season for rice crop. The others farmers did not use herbicides because of the high cost of herbicides, lack of awareness, inability to operate sprayers, lack of capital and non-availability of effective herbicides. The majority of farmers at Houinga who used herbicides, used glyphosate and 2,4-D Amine Salt. Glyphosate is a non-selective post-emergence (weeds) used in land preparation, and results in total vegetation control. Glyphosate is more effective against perennial weeds because it translocates to the underground rhizomes. 2,4-D is a selective post-emergence (rice) targeting broadleaved weed species. The main reasons farmers used herbicides were that they were labor saving and were much more efficient than hand weeding.

Burning of residues has been practiced by small-scale farmers for decades. Residues' burning in the tropics is a tradition linked to the slash-and-burn practices that has been handed down from one generation of peasant farmers to another as something that is beneficial to crop production (Akobundu, 1987). In the majority of rainfed lowland areas of the humid tropics, it has been a stable system, providing a limited number of people living on sufficient land as a continuing method of food production, requiring little in terms of inputs (Greenland, 1975). The primary purpose of field burning is to get rid of excess vegetation slashed before sowing, and weed control is an indirect benefit of this practice. According to farmers, burning is cheaper and easier than other methods of clearing. The slashed vegetation is left to dry for about one week before burning. As to burning, farmers are in favour of a rapidly advancing fire to be sure that all parts of the plot are touched. So they start burning early in the afternoon when there is some wind. Burning is rather superficial; often the slashed vegetation is not totally burnt. In that case, farmers pile up the remaining slash for a second burning. Farmers considered as more suitable for burning, large residues of grasses such as *Imperata cylindrica*, *Brachiaria* spp., *Paspalum scrobiculatum*, and *Rottboellia cochinchinensis*, and sedge *Cyperus distans*. Because for those weeds, slashing takes little time and the slashed vegetation dries out quickly, even when the first rains have started. This is due to the relatively low water content and the absence of thick stems in these species.

For most farmers, the indigenous practice of hand hoeing (shallow tillage) used for plowing before sowing was not considered as beneficial for succeeding hand weeding operations. Some farmers cited the manual tillage as beneficial to the weeding of *Rottboellia cochinchinensis*, because this weed has hairy and irritating stem, which makes it difficult to handle during weeding.

The study found that farmers did not depend on any single practice but combined various practices in an integrated manner to get more effective suppression of weeds. But in general, most farmers indicated that they could not develop sustainable management strategies for weeds because they do have adequate resources. And the results of a technography study conducted in Benin indicated that in spite of existing indigenous knowledge and technical recommendations, farmers expressed an urgent need for innovations in weed management that are both technically successful and socially acceptable (Kossou et al., 2001).

For auxiliary weeds, species such as *Alternanthera sessilis*, *Corchorus aestuans*, *Talinum triangulare* and *Eclipta prostrata* were purposely left in the field or removed before the actual weeding operations, as they were used for human consumption, medicinal uses or other domestic uses, a practice that has been reported before (Rodenburg et al., 2012). For instance, Achigan-Dako et al. (2011) reported the use of *A. sessilis*, *T. triangulare* and *Corchorus* spp. as vegetables in Benin. *Eclipta prostrata* was used by farmers as anti-venom against snakebite (Pithayanukul et al., 2004). *Imperata cylindrica* and *Panicum maximum* are used as roofing material for construction (Akobundu, 1987).

4.3.5. Conclusion

Regarding farmers' perceptions issues on weeds along the heterogeneous catena, farmers in the three studied areas differentiated up to 27 weed species and expressed their perceptions about their importance and mechanisms of control. Not all weeds are perceived as noxious. Some are considered as useful components in the system, even constituting vegetables during the hungry gap period. This fact suggests that weed control methods which require chemical technology in eradicating all types of weeds might not be acceptable to farmers in intensified cropping systems, as long as no other sources of wild vegetables are available. Thus, the development of economically viable, environmentally benign weed management strategies is a major challenge facing the smallholder farmers in inland valleys rice-based systems of West Africa.

Chapter 5

Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Cote d'Ivoire

5.1. Introduction

In West Africa, rice has been grown and consumed for thousands of years, and has long been an important component of both cropping systems and diets in countries such as Sierra Leone, Liberia, Guinea, Guinea Bissau and Cote d'Ivoire. Recently, rice has become a staple food for both urban and rural consumers throughout much of the sub-region. In 2007, Sub-Saharan Africa (SSA) imported more than 10 million tonnes of milled rice worth an estimated US $ 5 billion (Seck et al., 2012), which represents a serious drain on foreign currency reserves, aggravating the poverty and food security situations. Recently, several African countries have been ranked among the highest in the world in terms of rice imports as domestic production fails to keep pace with a demographic growth rate of up to 4% per year and changing consumer preferences (Balasubramanian et al., 2007), and due to income increases in urban areas, resulting in a shift of consumers' preferences in favour of rice. Unless the growth rate of domestic production is accelerated, SSA import-dependence is expected to widen in the future.

Despite an estimated 20 million small-scale rice farmers mostly cultivating rice in upland ecosystems in West and Central Africa, the lowlands in the inland valleys are likely to absorb much of the growing pressure on land for rice crop production (Windmeijer and Andriesse, 1993). Today, about 38% of the total rice area in West Africa is located in rainfed lowlands, but this share is rapidly increasing (AfricaRice, 2011). Only about 17% of the lowland rice-growing area is irrigated, while the major share is produced in traditional, non-bunded swamps in inland valleys and flood plains. This stands in stark contrast to Asia, where about 57% of the harvested rice area is under irrigation, but where there is little scope for further area expansion. In Africa, on the other hand, large lowland areas are potentially appropriate for rice cultivation, of which the major share is currently unexploited. With rice prices reaching a 30-year to record highs in 2007-2008 (AfricaRice, 2011), promoting domestic production ranks high in the policy agenda of most West African countries. Given their relatively high soil fertility and moisture availability, lowland ecosystems offer ample opportunities for area expansion and intensification. However, favourable soil and hydrological conditions may differ within the same wetland between the hydromorphic valley crests with sandy soils and a water table within the top 60 cm of the soil profile during the rice-growing period, and the near-permanently flooded fluvial or alluvial clay areas close to the centre of the valley bottom. In addition, weed infestation (Kent and Johnson, 2001; Rao et al., 2007) and nutrient imbalances (Becker et al., 2003) are frequently reported to limit the production. Intensification of lowland rice production in West Africa is generally based on simple interventions to improve water availability, control weeds, and correct nutrient imbalances. They involve the building of field bunds to retain rainfall water, and an increased use of family labour for weeding (Becker and Johnson, 2001). Purchased inputs such as mineral fertilizers and herbicides tend only to be applied in areas with favourable infrastructure and access to markets.

We hypothesize that the crop response to better water control, application of mineral fertilizer and improved weed control will depend on interactions of environmental factors and management interventions, and is likely to vary with the hydric regime of a given landscape position in the valley. The objectives of the present study were to comparatively evaluate at various landscape positions within an inland valley a number of technologies commonly applied in the Guinea savanna zone of Cote d'Ivoire. These involve the building of field bunds, chemical weed control, the use of improved high-yielding varieties, the application of mineral N fertilizer, and combinations of these.

5.2. Materials and methods

5.2.1. Experimental sites characteristics

The impact of lowland development on rice yield and input use efficiency was determined at the Africa Rice Center – Inland Valley Consortium key site of Poundjou (Boundiali) in the moist savanna zone of Cote d'Ivoire (9.5°N, 6.3°W) during two years. The key site was selected as being representative for rainfed lowland rice-growing conditions in the savanna environments of West Africa with fine-textured Gleysols in typically large valleys on schist parent material. According to the analytical procedures of the International Institute of Tropical Agriculture (1989), the average chemical analysis of topsoil 0–20 cm showed soil pH in water 1:1 = 5.2, organic carbon content of 20.4 (g kg^{-1}), total nitrogen 1.56 (g kg^{-1}). The textural class of the soil is clay loam, and the soil is classified as Gleysol (FAO, 1998). The valley comprises a watershed of seven third-order valleys, covering approximately 80 km^2, and containing four villages. The annual rainfall varies between 1200 and 1400 mm. The amount of rainfall received during the crop growth of the study period was 1050 mm in 1997 and 1300 mm in 1998. A detailed description of the experimental site is provided in Table 14. The valley bottom has a concave shape with the valley centre lying slightly lower than the valley crests. This valley bottom topography results in an irregular depth and duration of soil flooding depending on the plot location.

Table 14. Characterization of the experimental site and its rice-based production system.

Location	
Administrative centre	Boundiali
Village/watershed	Poundjou
Longitude (^{o})	6.3 W
Latitude (^{o})	9.5 N
Climate	
Agro-ecological zone	Northern Guinea savanna
Length of growing period (days)	210
Annual rainfall (mm)	1200-1400
Rainfall distribution	monomodal
Mean air temperature (^oC)	26
Mean maximum air temperature (^oC)	38
Global radiation (MJ m^{-2} d^{-1})	24
Potential evapo-transpiration (mm)	1650
Soil	
Soil order †	Gleysol
Parent material †	Schist
Textural class †	Clay loam
pH (H_2O)‡	5.2
Organic carbon (g kg^{-1})	20.4
N total (g kg^{-1})	1.56
C/N ratio	13.1
Available P (mg kg^{-1})§	3.5
CEC (meq 100 g^{-1} soil)	6.4
Production system ¶	
Ethnic group	Senoufo
Tillage	Manual/oxen/tractor
Seeding method	Dibble/transplanting
Rice varieties	Traditional/± improved
Input use	None
Production objective	Subsistence/ (sale)
Decision maker	Woman
Role of the system in Cote d'Ivoire¶	
Area (1000 ha)	56
Share of rice-growing area (%)	18

† Adapted from Windmeijer and Andriesse (1993).
‡ Soil: solution ratio = 1:2.5.
§ Bray I.
¶ Adapted from Becker and Diallo (1992).

5.2.2. Experimental layout and treatments

A half-hectare area of a third order stream valley bottom was selected. This valley bottom was divided into three distinct catena positions (valley centre, hydromorphic fringe, valley crests) based on the ponded water depth and the distribution of natural vegetation. After establishment of a detailed topographic map, one half of the valley bottom (0.25 ha) was developed through simple contour bunding (about 500 m^2 areas for each contour level) while the other half was left unbunded (Figure 46). Plot-level bunding involved the construction of semi-permanent earthen bunds of 40 cm height around (sub-) plots of 6 x 4 m. Four treatments were compared in three replications at each level of land development and catena. These included (1) traditional rainfed varieties (flood-tolerant cv. Gambiaka in the valley centre and drought-tolerant cv. Katiali in the hydromorphic fringe and valley crests) with farmers management (one hand weeding, no input use); (2) modern varieties (flood-tolerant cv. WITA 6 in the valley centre and drought-tolerant cv. WITA 4 in the hydromorphic fringe and valley crests) with farmers management (one hand weeding, no input use); (3) modern varieties with herbicide use (pre-sowing glyphosate as 5 litres ha^{-1} Roundup and early-post emergence oxadiazon as 4 litres ha^{-1} Ronstar 25 EC; and (4) modern varieties with herbicide and mineral fertilizer use (60 kg urea-N in two split applications at sowing and before panicle initiation). The field area was ploughed and harrowed using ox-drawn implements. Phosphorus (12 kg P ha^{-1}) and potassium (30 kg K ha^{-1}) were homogenously applied across the whole experimental area and incorporated during final harrowing. In the bunded sections, plots were levelled manually after soil saturation. Pre-germinated rice was dibble-seeded at 20x20-cm spacing and thinned to four seedlings per hill at 14 to 18 days after seeding (DAS) to give a final population of 10^6 plants ha^{-1}.

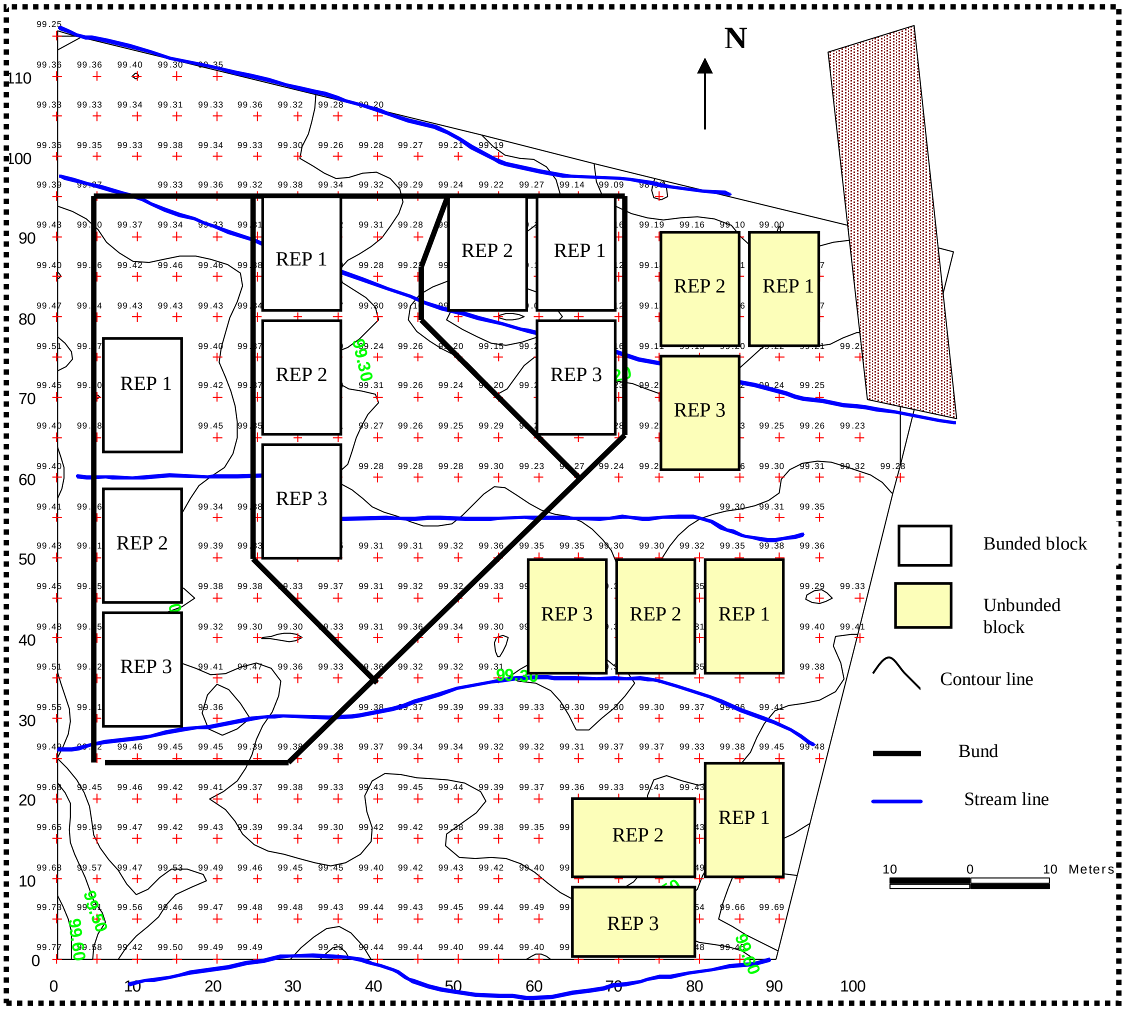


Figure 46. Experimental set up and contour map.

5.2.3. Sampling and measurement

Soil samples (0-20 cm) were taken at the beginning of the cropping season (comprising composites of eight sub-samples taken along a transect) and analyzed for pH (soil: H_2O ratio = 1:2.5), organic carbon (dichromate oxidation), total N (micro-Kjeldahl), available P (Bray I), and cation exchange capacity. Rice grain yield was determined from 2 m x 3 m areas and corrected to 14% moisture content. The agronomic N use efficiency of applied mineral N – NUE was calculated as (rice grain yield increase over the unfertilised control) * (kg mineral N applied)$^{-1}$. Weed species and aboveground weed dry biomass were determined from a predetermined 2 m^2

area in each plot at 28, 56, and 84 DAS. The depth of the ponded water was recorded at weekly intervals.

5.2.4. Statistical analysis

The impact of catena position on the composition of the weed community at 56 DAS was determined by a multivariate cluster analysis (SAS Institute, 2004). A mixed model procedure using the restricted maximum likelihood method (REML) estimated the variance between years. The covariance was used to test for the effects and interactions of study year and bunding, and for catena effects and factor interactions within years. The pooled residual error term was used to test treatment effects and their interactions. When three-way interactions were significant ($p <$ 0.05), single effect differences were evaluated by Least Significant Difference (LSD), examining the influence of bunding on rice yield and weed biomass and the effect of bunding on mineral N use efficiency along catena positions.

5.3. Results

5.3.1. Rice grain yield

The grain yield of rainfed lowland rice differentially responded to the position of the plots in the valley and to the various management interventions (Figure 47). Under farmers' management (unbunded plots, no external input use), grain yield increased from the valley crests towards the valley centre from 0.5 to 1.0 Mg ha^{-1} in the drier year of 1997 and from 0.7 to 1.3 Mg ha^{-1} in the wetter year of 1998 (Figure 48). The modern compared to traditional varieties was associated with an average yield reduction of 0.1 (1997) and 0.5 (1998) Mg ha^{-1}, across valley positions. The construction of shallow field bunds significantly increased the grain yield (Table 15), by 0.1-0.3 Mg ha^{-1} in 1997 and by 0.3-0.4 Mg ha^{-1} in 1998, irrespective of plot position in the valley and cultivar type. Improved weed control by herbicide application was beneficial at all valley positions and in both unbunded and bunded plots in 1998. During the drier year of 1997, significant herbicide effects in unbunded plots were restricted to the higher catena positions (hydromorphic fringe and fringe). The application of mineral fertilizer N provided little to no grain yield gains in unbunded fields but significantly increased the yield by 30-80% in the bunded plots, except for the lowest catena position in 1998, when the water level in the valley over-flowed the bunds in the valley centre. The grain yield with fertilizer application ranged from 1.2 (fringe) to 2.7 (centre) Mg ha^{-1} in 1997, and from 1.5 (fringe) to 3.9 (middle and centre) Mg ha^{-1} in 1998.

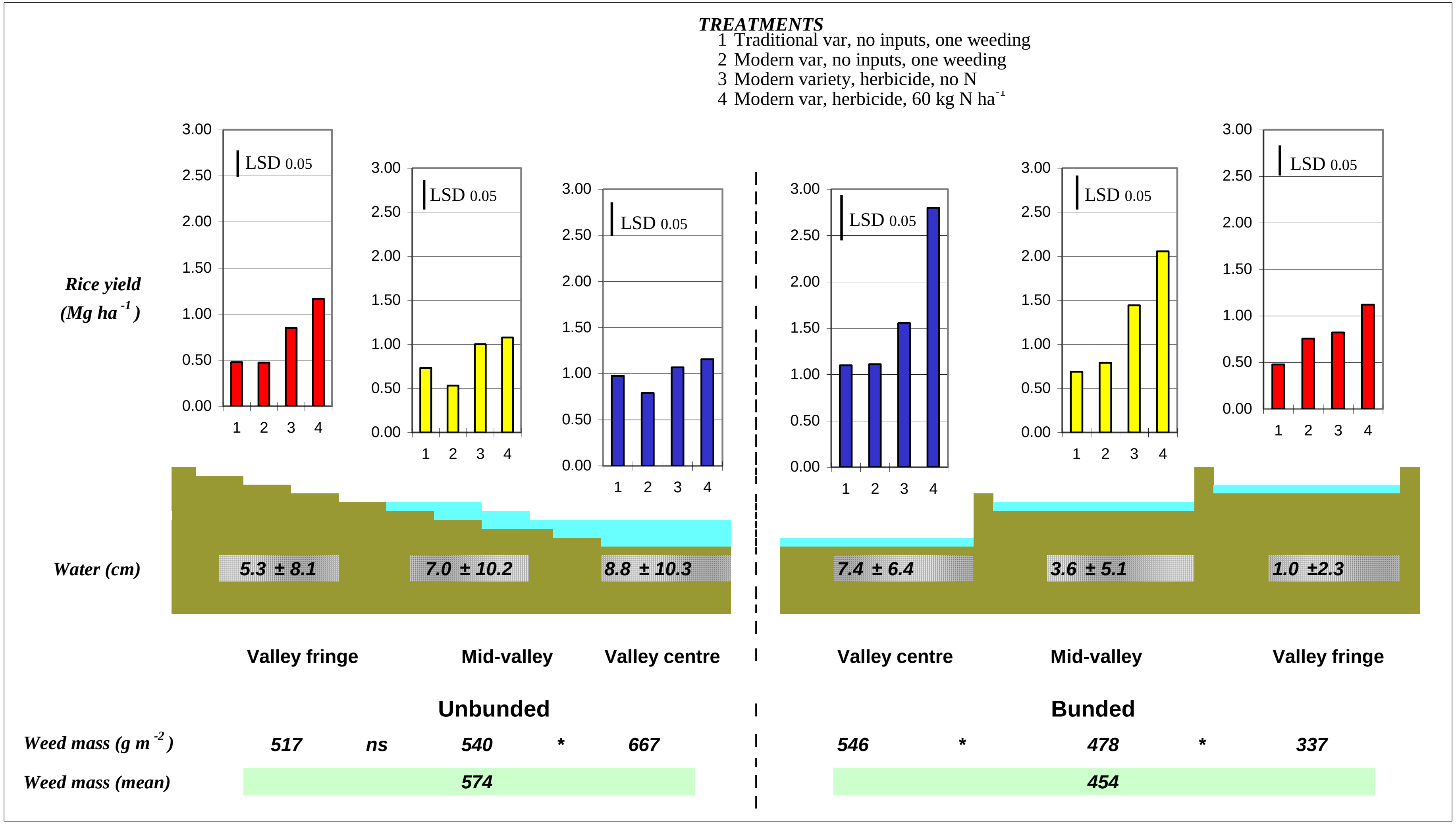


Figure 47. Effect of lowland development and crop management on rice grain yield, weeds and water level. Boundiali, year 1 wet season.

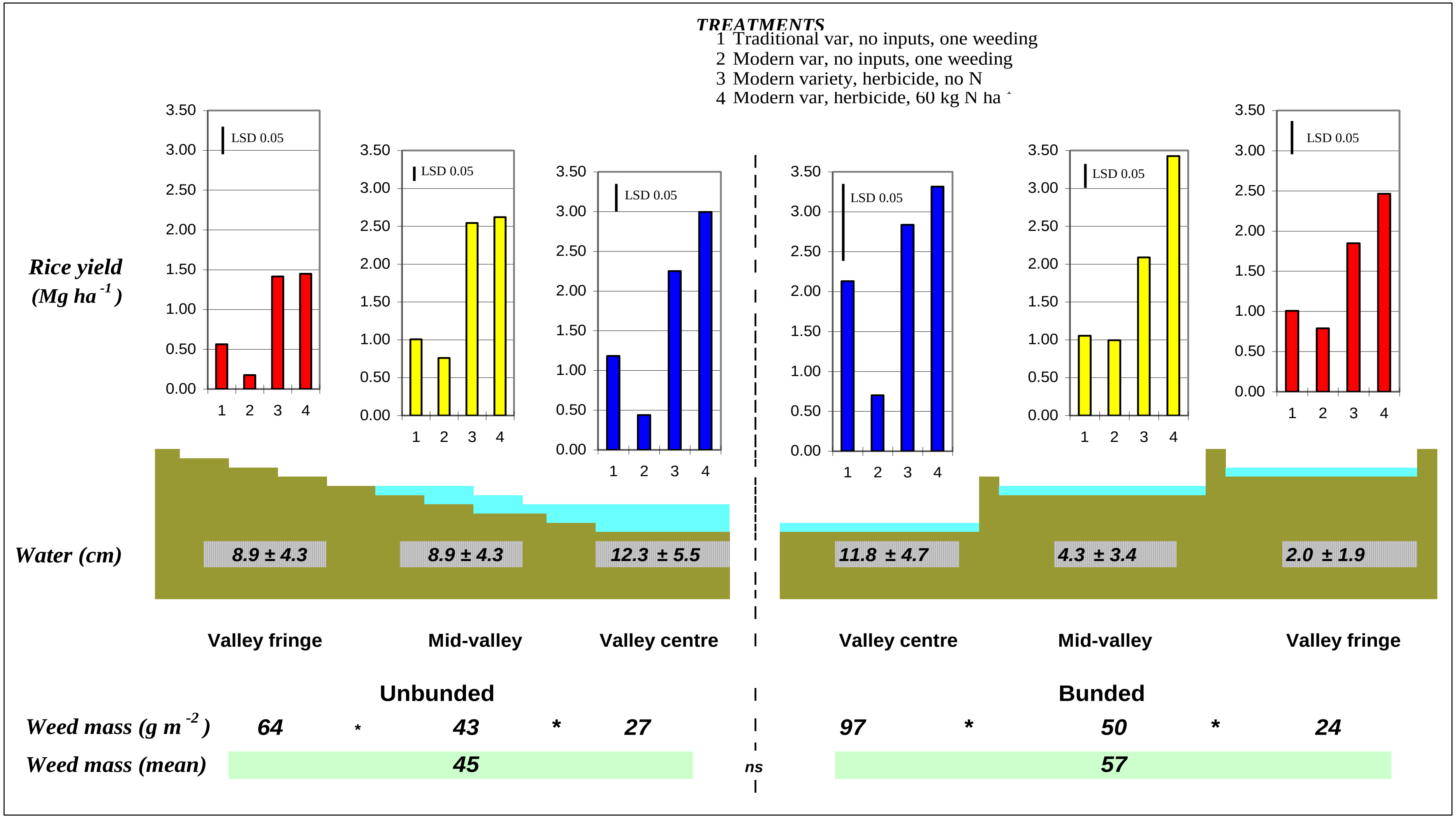


Figure 48. Effect of lowland development and crop management on rice grain yield, weeds and water level. Boundiali, year 2 wet season.

Table 15. Analysis of variance from mixed model procedures for yield of rice cultivars as influenced by year (Y), bunding (B), catena (Ca), and treatments (Trt), 1997 and 1998.

Source of variation	DF	DDF	F probability
Year (Y)	1	4	0.001
Bunding (B)	1	4	0.005
Y × B	1	4	ns
Catena (Ca)	2	16	<0.001
Y × Ca	2	16	ns
B × Ca	2	16	<0.001
Y × B × Ca	2	16	<0.001
Treatments (Trt)	3	72	<0.001
Y × Trt	3	72	<0.001
B × Trt	3	72	<0.001
To × Trt	6	72	<0.001
Y × B × Ca × Trt	21	72	<0.001

d.f.: degree of freedom; DDF: denominator degree of freedom of covariance parameters; ns, not significant at the <0.05 probability level.

5.3.2. Nitrogen use efficiency

The reported differences in yield response to fertilizer are reflected in the agronomic use efficiency of applied mineral N (A-NUE, Table 16). In unbunded fields, N application generally had no economic benefit with <4 kg grain (paddy) per kg N applied (cost equivalence of 3.7 kg paddy grain and 1 kg urea-N at the price level of 2000 and of 3.9 at the price level of 2008 (FAO, 2010). The only exception occurred in the unbunded plots of the valley centre in 1998. Bunding resulted in significant gains in N use efficiency with applied mineral N in all but the plots in the valley crests during the dry year of 1997. The A-NUE gains due to bunding averaged 10-12 kg grain kg^{-1} N and were higher in the valley centre than in the fringe positions. Improved weed control was reflected in an increased A-NUE of 5-6 kg kg^{-1} N. In contrast to bunding, the weed control-related effects on A-NUE tended to be greater in the hydromorphic fringe than the centre positions.

Table 16. Effect of field bunding, catena position on the agronomic use efficiency of applied mineral N fertilizer (field trial 1997 and 1998).

Year	Position in the valley	A-NUE (kg grain kg^{-1}N)			Gain of bunding	Gain of weeding
		unbunded		bunded		
1997	Valley crests	3.6	ns	5.1	1.5	2.3
	Hydromorphic fringe	1.2	*	10.2	9.0	7.4
	Valley bottom	1.6	**	22.2	20.6	5.5
	Mean	2.1	**	12.5	10.4	5.1
1998	Valley crests	0.6	*	10.2	9.6	1.0
	Mid- valley	1.3	**	12.4	11.1	9.5
	Valley bottom	8.0	**	23	15	6.7
	Mean	3.3	**	15.2	11.9	5.7

5.3.3. Plot water level and fluctuations in ponded water depth

The distinct differences of yield and A-NUE by valley position and bunding were closely related to the plot water regime (Table 17). While the mean ponded water depth in the fields increased from the valley crests (1-9 cm) towards the valley centre (8-12 cm), they also became increasingly variable in time, with fluctuations of 0-34 cm in 1997 and 0-26 cm in 1998. The construction of field bunds only slightly increased the mean ponded water depth in the fringe and the centre positions of the valley, but substantially reduced fluctuations in ponded water depth to 8-18 cm in 1997 and 6-19 cm in 1998. This regulation of the hydric regime by bunding (reduction in the standard deviation of the ponded water depth by factors of 1-4 of bunded versus unbunded plots) was associated with the observed increases in grain yield and in the efficiency of applied mineral N.

Table 17. Effects of catena position and field bunding on seasonal fluctuations of ponded water depth (field trial 1997 and 1998).

Year	Position in the valley	Lowland development	Water table (cm)		
			Mean	(Range)	STDEV
1997	Precipitation: 1050 mm during growing period				
	Valley crests	unbunded	5.3	(0-27)	8.1
		bunded	1.0	(0-8)	2.3
			**		**
	Hydromorphic fringe	unbunded	7.0	(0-33)	10.2
		bunded	3.6	(2-18)	5.1
			*		*
	Valley bottom	unbunded	8.8	(1-34)	10.3
		bunded	7.4	(2-20)	6.4
			ns		*
1998	Precipitation: 1300 mm during growing period				
	Valley crests	unbunded	8.9	(0-21)	4.3
		bunded	2.0	(1-7)	1.9
			**		**
	Hydromorphic fringe	unbunded	10.8	(2-23)	4.9
		bunded	4.3	(1-9)	3.4
			*		*
	Valley bottom	unbunded	12.3	(2-26)	5.5
		bunded	11.8	(2-21)	4.7
			ns		**

^{ns} $p > 0.05$; * $p < 0.05$; ** $p < 0.01$.

5.3.4. Weeds species and effects of weed control

There was greater weed biomass in the first year than in the second, and the construction of field bunds tended to result in a reduction of weed biomass, though the effect was not consistent across position and years. Weed species composition differed between catena positions but was largely unaffected by the agronomic management. Weed biomass at either 56 or 84 DAS was not significantly affected by input use and cultivar choice, but the response differed between the study years, as there were indications of an effect in the second year treatments. The catena effects on species composition (Figures 47 and 48) and the effects of the hydric regime on weed biomass for the two study years are presented in Table 18. The composition of the weed flora associated with rice varied by landscape position in the valley bottom and was assumed to be largely related to soil moisture, and the depth and duration of flooding. The hierarchical cluster analysis indicated 4 distinct clusters (Figure 49). Cluster 1 was dominated by *Cyperus* spp (CYPSP), *C. haspan* L. (CYPHA) and *Ludwigia* spp. (*Ludwigia hyssopifolia* (G. Don) Exell and *Ludwigia abyssinica* Rich.) (LUDSP), and these species occurred along the whole catena. Cluster 2 comprised the dominant species in the valley bottom and included *Oryza longistaminata* A. Chev. & Roehr. (ORYLO) and *Spilanthes filicaulis* (Schum. & Thonn.) C. Adams (SPIFI). While *Fimbristylis littoralis* Gaudich. (FIMLI) and *Hydrolea glabra* Schum. & Thonn. (HYDGL) occurred at all catena levels, they were the dominant species (Cluster 3) on the valley slopes. Finally, *Ageratum conyzoides* L. (AGECO), *Echinochloa* spp (ECHSP) (largely *Echinochloa colona* L. and *Echinochloa obtusiflora* Stapf), *Paspalum scrobiculatum* L. (PASSC) and *Setaria pallide-fusca* (Schum.) Stapf & C.E. Hubbard (SETPA) were only encountered in the valley crests and were grouped into Cluster 4. These cluster grouping may serve to identify indicator species for prevailing wetland hydrological conditions and the targeting of agronomic interventions.

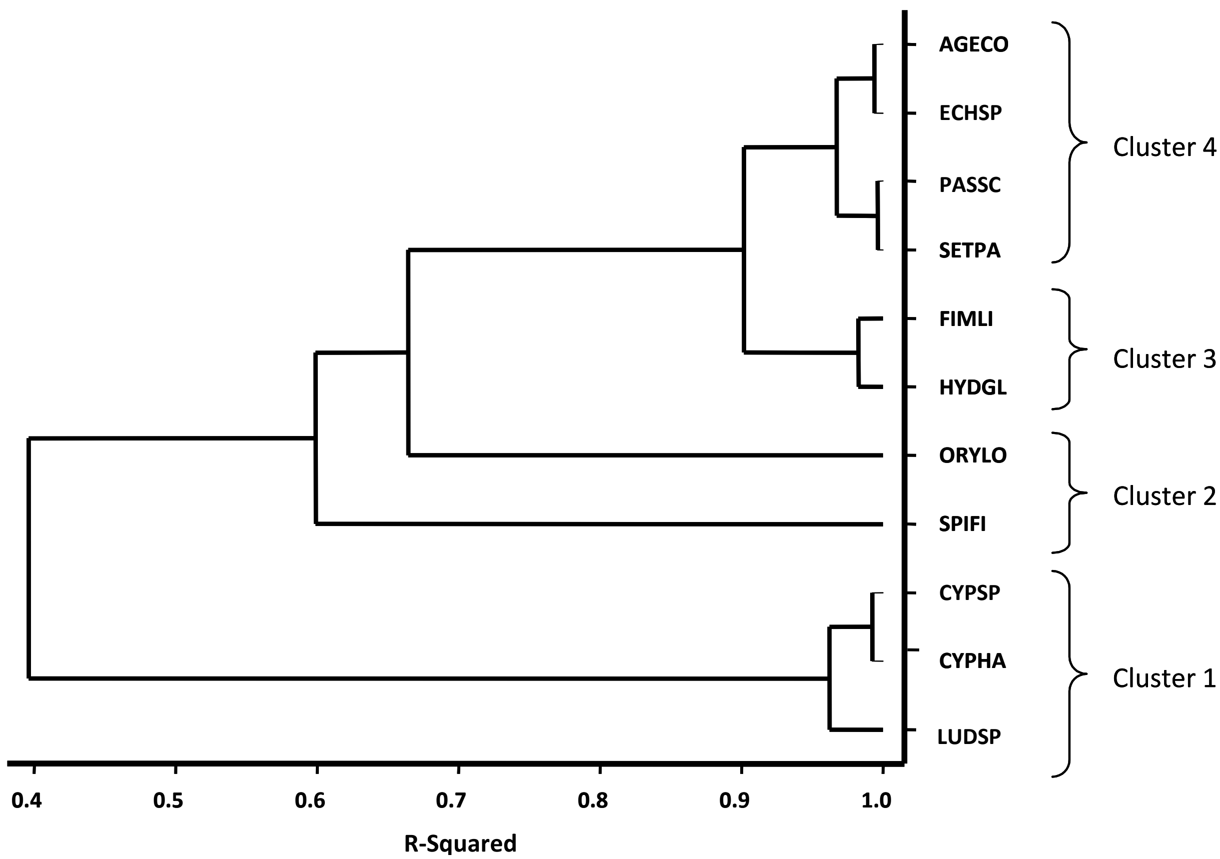


Figure 49. Dendrogram of major cluster groups of weed genera according to their occurrence within catena positions based on dry biomass at 56 DAS (field experiment, wet season 1997, Boundiali, Cote d'Ivoire). AGECO: *Ageratum conyzoides*; ECHSP: *largely Echinochloa colona and Echinochloa obtusiflora*; PASSC: *Paspalum scrobiculatum*; SETPA: *Setaria pallide-fusca*; FIMLI: *Fimbristylis littoralis*; HYDGL: *Hydrolea glabra*; ORYLO: *Oryza longistaminata*; SPIFI: *Spilanthes filicaulis;* CYPSP: *Cyperus* spp.; CYPHA: *Cyperus haspan*; LUDSP: *Ludwigia abyssinica*.

The dry biomass of the weeds associated with rice was determined at 28, 56 and 84 days after rice seeding. As the biomass at 28 days was consistently <10 g m^{-2}, data are not presented here. The weed mass varied strongly between catena positions, water control treatments, and study years. In unbunded plots the weed biomass at 56 days was high at the valley crests with frequent alternate soil drying and wetting cycles and much lower in the more permanently flooded lower catena positions (only significant in 1997). This trend was reversed at 84 days after seeding with the highest weed mass occurring in plots of the valley bottom where the wild rice species *O. longistaminata* dominated the weed mass (Figure 50). A similar (but not significant) trend was observed in 1998 but the weed mass was only one 10th to one 20th of the biomass in 1997 (Table 18). The construction of field bunds significantly reduced the weed biomass, particularly in the valley crests and mid-section. The effects of bunds on weed mass in the valley bottom were only observed in 1997. The weed biomass in 1998 was extremely low and there were no significant differences between treatments.

Figure 50. Women farmers piling up *O. longistaminata* residues after weeding fields located in valley bottom position at Pounjou (Boundiali).

Table 18. Effect of field bunding, catena position and varietal choice on weed biomass in lowland rice, and summary of statistical effects (field trial 1997 and 1998, Boundiali, Cote d'Ivoire).

Year	position	Dry weed biomass (g m^{-2})					
		56 DAS		84 DAS		Total	
		Unbunded	Bunded	Unbunded	Bunded	Unbunded	Bunded
1997	Valley crests	262	143	255	194	517	338
	Hydromorphic fringe	125	215	415	238	540	453
	Valley bottom	132	165	585	382	717	547
						0.003	
	Bunding (B)	ns		0.000		0.003	
	Catena (Ca)	0.013		0.000		ns	
	Treatment (Trt)	Ns		ns		ns	
	B x Ca	0.000		ns		ns	
	B x Trt	ns		ns		ns	
	To x Trt	ns		ns		0.008	
	B x Ca x Trt	0.043		0.012			
1998	Valley crests	39	13	25	11	64	24
	Hydromorphic fringe	289	33	20	18	43	50
	Valley bottom	0	52	27	45	27	97
	Bunding (B)	0.041		ns		ns	
	Catena (Ca)	ns		0.006		0.029	
	Treatment (Trt)	ns		ns		0.023	
	B x Ca	<0.001		0.040		<0.001	
	B x Trt	ns		ns		ns	
	Ca x Trt	ns		ns		ns	
	B x Ca x Trt	ns		ns		ns	

ns; not significant at the <0.05 probability level.

5.4. Discussion

In contrast to Asia, rice in West Africa is grown to a large extend in open, non-bunded fields, mainly in inland valleys of the moist savanna zone (Becker and Diallo, 1992). In addition, poor infrastructure and the relative remoteness from markets results in a low use of external inputs and the widely encountered subsistence orientation of rainfed rice production.

5.4.1. Catena effects

Typically, the West African rainfed environments are characterized by different landscape positions within the same valley and consequently by a variable hydrology leading to variable yields of the typically traditional cultivars (Tsubo et al., 2006). As in the present study, the hydrology and soil aeration status is controlled by the climate and the morphology or topography of the valley, whereby the main sources of water are precipitation, surface flow (runoff from the uplands) the over-flooding of the central valley stream. In the valley crests, large fluctuations in ponded water depth may have led to transient drought, and the low agronomic use efficiency of the applied mineral N may have been caused by N losses due to leaching, run-off, and denitrification (Becker et al., 2007). In addition, water stress (both transient drought and deep inundation) reportedly reduces N uptake and grain yield of rainfed rice (Castillo et al., 1992; Tuong et al., 2002; Wopereis et al., 1996). Thus, strong yield differences were observed between the fringe and the centre of the valley in the present study. The absence of such catena effect on rice yield was reported from Indonesia and Thailand by Boling et al. (2008), who attributed this to the fact that farmers' practices were already fine-tuned to their field-specific conditions. This is definitely not the case for West African savanna ecosystems, where farmers' technicity level is generally low and where site-specificity of management strategies is largely absent.

While most rice in the rainfed wetlands of SSA is grown for subsistence purposes in such unbunded fields with little use of external inputs, a gradual shift towards a more market-oriented production can be observed in some areas (Becker and Johnson, 2001). This shift is accompanied by the use of improved methods of land preparation such as land levelling by draft animals or tractors and the building of field bunds, and a growing use of modern varieties and external inputs (Hirose, 2002; Moormann and Juo, 1986).

5.4.2. Bunding effects

The present study confirmed the generally variable hydrology by landscape position, which was associated with high weed pressure and low rice yields. Consequently, the positive effects of bunding on yields also varied by year and landscape position in the valley bottom. In other studies in West Africa, bunding reportedly reduced the weed biomass associated with the rice crop, while substantially increasing the yield (Becker et al., 2003). Maintaining soil flooding through bunding can further increase the availability of P and certain micronutrients and provide a more neutral soil pH leading to higher rice grain yields (Asubonteng et al., 2001; Issaka et al., 2009). Yield increases due to improved water control in the range of about 40% have also been shown from rainfed environments in the humid forest zone of West Africa (Becker and Johnson, 1999a). Generally, bunding can maintain a more constant water level within the plots, which in the present case was associated with a reduced weed biomass and increased agronomic N use efficiency.

5.4.3. Mineral nitrogen effects

Nitrogen deficiency in rainfed rice is usually associated with fluctuating depths of the ponded water and the resulting N losses from the soil (Haefele et al., 2008). Alternate drying and wetting cycles of the soil (as typical for unbunded rainfed plots) can stimulate mineralization of soil organic matter (Cassman et al., 1996) and increase (both native and applied fertilizer) N losses (Becker et al., 2007; George et al., 1993) and can induce a general soil fertility decline, resulting in low yields (Tsubo et al., 2006). On the other hand, mineral fertilizers combined with proper water management can be used to improve fertility management and N use efficiency. Thus, reduced fluctuations in ponded water depth and the maintenance of sustained flooded soil conditions increased NUE in Asian lowlands (Cassman et al., 1996).

The construction of bunds and proper timing of fertilizer N application reportedly increased the N use efficiency in farmers' fields in Ghana (Asubonteng et al., 2001) and in Nigeria, where the combined use of bunding and modern rice cultivars increased the yield response to mineral N from 35 to 40% above that of traditional varieties (Ashraf et al., 1988). Under high-input conditions, the tall traditional varieties are more susceptible to lodging and less responsive to nitrogen than modern semi dwarfs, leading to yield reduction. Modern cultivars, on the other hand can better take advantage of weed control and input use (Ladha et al., 1998).

Economically, the profitability of fertilizer use is assessed using the value cost ratio (VCR), which compares the gross income attributable to fertilizer with the costs of fertilizer. Typically, the financial incentive for applying fertilizer is considered adequate when the VCR is greater than two (Yanggen et al., 1998). In the present case, the value of paddy rice gain due to fertilizer application and the cost of urea-N are about equal (VCR of 1) in the unbunded plots, both for the 2000 and the 2008 price levels. Values of the VCR of >2 are only reached in the bunded plots of the lower catena positions, indicating that mineral fertilizer use is economical only after bunding of the plots and appears in no case an economically viable option in the valley crests. This assessment of 2000 holds also true in 2008, when temporarily increased paddy prices were offset by increased input costs (AfricaRice, 2011; FAO, 2010).

5.4.4. Weed effects

Principal weed species in this study are among the major of weeds of direct seeded tropical rice world-wide (Rao et al., 2007). Further, species occurring in this study reflects the principal weeds cited by farmers in a survey of farmers' perception of pests conducted in the Boundiali region in 1992 (Adesina et al., 1994). In that study *A. conyzoides*, *Fimbristylis* spp., *E. colona*, *P. scrobiculatum* and *Oryza* spp were all cited as principal weeds of rice. Cropping systems and levels of intensification have been reported to impact on species composition and Kent et al. (2001) showed that *Cyperus difformis* and *C. iria* were particularly abundant in the savanna systems. These authors also associated these weeds with sustained flooding and intensification, while *Cyperus rotundus* and *Cynodon dactylon* were associated with rice followed by dry season cropping.

The effect of reduced fluctuation in ponded water depth and the maintenance of sustained flooded soil conditions reportedly reduce weed biomass (Becker and Johnson, 1999a; Williams et al., 1990). Weed biomass in the present study varied widely between 45 and over 475 g m^{-2}, depending on year, position of plots in the lowland catena, and water control. Kent and Johnson (2001) reported that a shallow flooding of 2 cm is sufficient to reduce the emergence and growth of a number of weeds such as *Fimbristylis littoralis* and *Echinochloa* *colona*. The importance of water control and land levelling for controlling weed growth in rainfed lowland rice has also been shown from other studies in Asia (Moody, 1996) and West Africa (Izac and Tucker, 1991; Touré et al., 2005). The apparent contradiction to this in the results of the present study where weed biomass increased with flooding depth is likely to be attributable to the dominance of the aquatic perennial wild rice *O. longistaminata*, which favours wet conditions and withstands prolonged flooding (Kent et al., 2001). A study in the forest-savanna transition zone (approximately 150 km south of the present study), showed that *A. conyzoides* formed the greatest part of the weed biomass in rice grown on the hydromorphic / valley crests in the first two years of rice but this was succeeded by *Cyperus rotundus* L, *Euphorbia heterophylla* L. and *Digitaria horizontalis* Willd. in later years (Johnson and Kent, 2002). There were less changes in the rainfed lowland area of the same study, however, and *Cyperus difformis* L., *Leersia hexandra* Sw., *A. conyzoides* and *Fimbristylis littoralis* persisted as the dominant weeds over five seasons. The present study was not conducted over a sufficiently long period in order to record changes in species but the indications from other studies are that changes to management, flooding regime and cropping may all influence weed species composition. Ideally, weed management strategies should be designed and developed so that they anticipate and address likely changes in the species composition (Rao et al., 2007). This would contribute to the sustainability of systems but would require further detailed study of the response of weed populations to a range of management systems over time.

Farmers in the savanna zone have considerable awareness to the use of herbicides, and other inputs, as these are widely used in the cotton crop (Fleischer et al., 1998). In a survey of rice farmers' management strategies, conducted in the Boundiali region in 1992, 55% of farmers reported the use of herbicides, and 95% still relied to some extent on hand pulling (Adesina et al., 1994). The major reasons given for the use of herbicides was efficiency of control and labor saving. Incentive for herbicide use is likely to grow as farmers seek labor saving options in order to reduce costs and improve returns to labor.

As reported in a previous study in Cote d'Ivoire, total labour requirements for a single hand weeding ranged from 250–780 man h ha^{-1} (Stessens, 2002). The use of herbicide as substitutes for hand weeding can result in considerable savings to the farmers. Furthermore, rice yields can greatly improve with herbicide application, considering that hand weeding is frequently undertaken at a too late stage of crop development when serious crop-weed competition has already occurred. However, such input-dependent intensification strategies (both herbicide and fertilizer use) are likely to occur only with access to input and output markets, the availability of capital in the household, and in areas where land is becoming a limiting production factor.

5.4.5. Specifics of African rainfed rice in inland valleys

While there are countless examples from Asia how to improve rainfed lowland systems, Asian technologies can only partially be applied to the African scenario. As indicated above, the rainfed environment in Africa is morphologically rather different from Asia. While most rainfed rice in monsoon Asia is grown on flat land, in the flood plains of the large rivers or on levelled terraces, the African rainfed rice is primarily produced in the undulating landscape of the inland valley, with differing catena positions along valley bottom slopes and large fluctuations in ponded water depth, both in space and time. Such diversity in hydric regimes leads to a different composition and a severe pressure of weeds. It may also explain the much lower and much more variable agronomic use efficiency of applied mineral N by African rainfed lowland rice with 2-10 kg grain kg^{-1} N applied (Becker and Johnson, 2001) compared to the Asian rainfed rice with 12-15 kg grain kg^{-1} N (Becker, 2008). This implies a spatially much more stratified targeting of technical options, considering not only soil type and climate as in the site-specific crop management of Asia (Aulakh and Grant, 2008) but also the taking into consideration of the catena position in the wetland and the access to inputs and markets (system-specific crop management).

5.5. Conclusion

On the heterogeneous catena of inland valleys in West Africa, simple water management structures such as bunds led to substantial weed biomass reduction and rice yield gains, especially if accompanied with good crop management practices.

Chapter 6

General discussion and conclusion

6.1. Introduction

Weed infestation, low soil fertility and poor water management are unavoidable components of farming systems in West African inland valleys. They have a large impact on small-scale farmers' production systems and constitute major constraints to their livelihoods, especially during the transitional phase towards continuous cropping, when fallowing periods are too short to suppress weeds and restore soil fertility, and in permanent cropping systems as encountered in inland valleys (Vissoh, 2006). On-farm surveys and key sites trial were conducted in Benin and Cote d'Ivoire for the improvement of integrated crop management. The process included studying weed communities and weed management practices and agronomic (weed) management of lowland rice along the heterogeneous catena. This concluding chapter reflects on and analyses (1) the heterogeneity of biotic and abiotic factors encountered along the catena (2) the composition of weed flora in Guinea savanna inland valleys of southern Benin and northern Cote d'Ivoire and (3) the crop management technologies in inland valleys.

6.2. Heterogeneity

The heterogeneity in inland valley starts with the catena and the diverse production units, and responds mainly to the two first hypotheses stated as follow:

- Hydric regime and/or cropping systems based on crop rotations may influence weeds communities and weed covers of a given landscape position along the heterogeneous inland valley catena

- Diverse production units may influence cropping practices along the heterogeneous inland valley catena and consequently weed species occurrence and abundance, and crops yields, and farmers' perception of weeds and vice versa

The inventory of natural resources on a landscape contributes to a better understanding of weed-soil-water-crop relationships (Chapters 4 and 5). The inventory produced land units (valley crest, hydromorphic fringes and valley bottoms) which are units characterized by a specific combination of vegetation, soil, geology, land form and land uses (De Rouw, 1991). For land uses and related management practices, farmers often utilize the heterogeneity along the catena to diversify their crops and to avoid labor constraints by spreading out their activities (Becker and Diallo, 1992). Richards (1986) noted that farmers in central Sierra Leone spread the risk inherent in agriculture by farming several positions in the catena. Farmers with a sufficiently long tradition of inland valley rice based production may also use different management practices at each catena position (Tsubo et al., 2006). On our study site in Benin, apart sowing rice and jute mallow at the lower position of the catena (valley bottoms with sufficient moisture), farmers had limited experience in rice and vegetables cultivations in inland valleys, thus no significantly different weed management methods were developed at each catena position (chapter 4). This non significance differences between the management methods at each catena position may have a link with the size of the inland valleys. In the study sites in Benin, inland valleys are very narrow with less evidence of the heterogeneity between the catena positions. The study in Benin was hindered by the small size of the valleys with different sections of the catena being very close. Moreover, only two sampling quadrats were used in each farmer field, which may have missed some heterogeneous biotic or abiotic factor. The study in Benin was also less statistically powerful for revealing heterogeneity between cropping systems, sites and farmers: no double rice monocropping (rice in rainy and dry season) check treatment was included, village position and cropping systems factors were confounded, factors studied (catena position and farming systems) were not equally present in each farmer's field. Contrast between the experimental sites in Benin for better revealing the heterogeneity was mitigated, because the sites were very close to each other (4 to 20 kilometers with the same agro ecology and near identical rainfall).

Whereas, in the northern Guinea savanna zone in Cote d'Ivoire with rectilinear topography, inland valleys tend to be wider (Windmeijer and Andriesse, 1993). In Cote d'Ivoire, extensive and systematic data collection, using aerial photography and satellite images, soil description, chemical analysis, water table depth measurements, full weed species lists and notes on crops and performances of crops provided scientific and statistical evidence for the heterogeneity of the landscape of the experimental site (chapter 5). The heterogeneities of the land along the catena are very important for crop production as was demonstrated in the field experiment conducted in Cote d'Ivoire (chapter 5). Crops react on the totality of environmental conditions. In this study, the relative positions of plant species have been determined along the different gradients on the catena. Thus it is known that common plant species have ecological preferences with respect to rainfall and related moisture and soil conditions. On a given position on the catena, there are plants that are expected to grow there, and there are plants that are not expected to grow there. Even farmers with limited experience in agriculture such as those in the study areas of Benin obviously have the same outlook, although knowledge of the flora seems to vary enormously from person to person and is usually confined to plants with highly indicative value in the places where that person (De Rouw, 1991). So plants have their normal position on the catena. Any plant occurring outside its normal range of habitats is perceived as an anomaly. Thus sites with plants indicating superior moisture conditions (valleys bottoms) were actively looked for rice cultivation, creating confounding effects between cultivated crops and position on the catena.

The diversity of the production units in small farms is largely determined by the social aspects of the production. The head of the farm is usually also the head of the production unit. He is normally the owner of the farm but in some cases a tenant. All or most decisions concerning the daily operations (e.g. sowing, weeding) as well as future development of the smallholding are taken by the owner. Some decisions, however, might be taken by a group of smallholders, e.g. by a water-users association (Beets, 1990).

6.3. Composition of weed flora of southern Benin and northern Cote d'Ivoire

The distribution of the natural weed flora of West Africa follows more or less the agro-ecological zonation for inland valleys in savanna areas (Windmeijer and Andriesse, 1993). There are ecological differences between the valley crest and valley bottoms of inland valleys. In the valley crests and bottoms, the water table fluctuates strongly; creating a wet environment in the rainy season and in the dry season, dry conditions with more or less deep water table. Thus water is the key factor determining weed species composition. There is a change in species composition along the slope of the catena linked to soil moisture. Although the research studies were conducted at different period of time and in different countries, the hypothetical climate change did not influence too much the occurrence of major weeds. For the sites in Benin and Cote d'Ivoire, the common major weed species occurred mainly in the valley crest and hydromorphic fringe positions: *Ageratum conyzoides*, *Echinochloa* spp (largely *Echinochloa colona* and *Echinochloa obtusiflora*), *Paspalum scrobiculatum* and *Setaria* spp.. For the other two catena positions, there were no common species; for example, *Oryza longistaminata* was only found in valley bottom position in northern Guinea savanna inland valley of Cote d'Ivoire; whereas *Sphenoclea zeylanica* was only found during the rainy season in valley bottom position in Benin. Although *Sphenochlea zeylanica* was common in both forest and savanna lowlands of Cote d'Ivoire as reported in a previous study (Kent et al., 2001). There were other common weed species for the sites in Benin and Cote d'Ivoire with undifferentiated ecological positions along the catena: *Cyperus* spp, *C. difformis*, *Ludwigia* spp. (*Ludwigia hyssopifolia* and *Ludwigia abyssinica*), *Fimbristylis littoralis* and *Hydrolea glabra* (Appendix D). The change in weed species population over a relatively longer period of times (more than two years) was not investigated at the sites in Benin and Cote d'Ivoire.

A characteristic common to those weeds found in inland valleys of Benin and Cote d'Ivoire is their ability to adapt to a wide range of environmental conditions. This response to the different environments is termed plasticity (Johnson, 1997). Account should be taken of this plasticity when designing weed management methods throughout West Africa inland valleys.

6.4. Better crop management in West African inland valleys

Better crop management responds to the third hypothesis stated below:

- Crops yield responses to improved weed control, better water control and application of mineral fertilizer, will depend on interactions of environmental factors and other management practices, and are likely to vary with the hydric regime of a given landscape position on the heterogeneous inland valley catena

The most common and judicious way of improving the water management of the field is to try to control partially water through bunding (raised compacted foot paths between plots) acting as a buffer, so that run-off is reduced and water is stored. Stabilizing the water supply in this way raises crop yields in several ways, mainly by helping to control weeds. Indeed, bunding has been used in the productive lowland rice systems of Asia and elsewhere. Total water control could be too expensive for smallholder farmers in West Africa, whereas partial water control through bunding offers a sustainable and affordable way of water management to farmers. Farmers can build bunds using hoes, at the same time as they prepare their seedbeds. The task requires little extra labor, which can be supplied from the family in the case of women with children or husbands living on the farm. Following bunding, land levelling is also important for inland valley development.

In this thesis, bunding reduced fluctuations in the depth of flooding and retained water in plots further away from the valley, providing more uniform growing conditions over a wide area (chapter 5). It increased yields by an average of 30% across the catena (chapter 5), reducing weed biomass by 25% (chapter 5). The increased yields, combined with the reduced labor requirement for weeding, should markedly increase the profitability of rice based production systems. Bunding interacted significantly with other treatments. Most marked was the effect on the efficiency of fertilizer use in the lower and middle parts of the catena (chapter 5). Fertilizer applied in open fields tends to get flushed way with escaping water. It also gets lost to the atmosphere, as the alternating wet and dry conditions oxidize it (Becker et al., 2007). The introduction of bunds prevented both sources of loss. But in the study conducted in Benin (chapter 4), weed management practices and the available options were often a function of biophysical and socioeconomic factors which, in turn, were determined by the agroecosystem. In the unbunded lowlands, weeds could not be controlled by flooding the soil surface (Rodenburg and Johnson, 2009)

In inland valleys, the timing of fertilizer applications and weeding also gave significant yield increases. Delayed first weeding affected negatively crop yields as for poor farmers with labour shortage early in the season (i.e. dominantly part time farmers with casual employment), and consequently weeding should be done earlier and preferably during the critical period. The critical weed-competition period for lowland rice in Senegal was between 29 and 32 days after seeding (DAS) during the rainy season and between 4 and 83 DAS during the dry season (Johnson et al., 2004). For most vegetables crops (tomato, okra, pepper and some leafy vegetables), it is at the first third of the crop cycle or the first 42 DAS (Akobundu, 1987). The solution to the problem of excessive losses due to weeds can also be through education and motivating of farmers to weed better (Beets, 1990). Although herbicide treatment had significant effect on increasing rice grain yield and reducing labour (Chapters 4 and 5), on the whole, it seems neither feasible nor necessary to try to solve the problem with the introduction of herbicides. These chemicals can simply not be afforded by most poor tropical smallholders. In most situations, better shaped hoes adapted to the prevailing conditions can ease weed control. For wealthier farmers with enough endowment and tradition with animal (ox), the introduction of animal-drawn weeding equipment can be considered. Even rotary weeders can also be purchased and used in order to save labour in weed management in inland valleys. These implements are often used in row sown crops providing rows are spaced wide enough and the implements are available to farmers (Rodenburg and Johnson, 2009). A shortcoming of such devices is that it does not target weeds in the row and when used close to the rice plant they may also cause crop damage. The timing of fertilizer applications had significant effects on rice plants. The rice plant uses nitrogen at two stages of its growth cycle: at 2-3 weeks after emergence, during early tillering; and again at panicle initiation, 65 day or so before harvest. Split applications at these two points in the cycle are far more efficient than a single application or than applications at other times. Thus improving water control through bunding is the starting point in releasing the potential of the lowlands including fertilizer, better weed management, and improved seeds.

As the above aspects concerning smallholder lowland rice based systems cannot overcome all the constraints faced by this ecosystem, for the time being it may be advisable to promote crop diversification through the integration of rice and vegetables and its effects on weed management (chapter 4). According to Erenstein (2006b), crop diversification is commonly a response to needs unrelated to weather variation and markets. Included here are needs for crop rotation (time scale) and intercropping (space scale), for a variety of feeds for livestock (e.g. fish production), and for even labour flow. Crop rotation is an important ecological tool for reducing constraints, particularly where fields are infested with soil-borne diseases or insects, and weeds. Rotation with a non-susceptible crop allows a period of sanitation during which inoculum declines through starvation, decay, or predation. Most plant pathogens are poor saprophytes and suffer from competition and attack by superior decay organisms when hosts are absent. For weed control, crop rotations play a long-term role by preventing particular weed species from adapting to the growth cycle of specific crops (Loomis and Connor, 1992). Also benefits can be obtained from weed control through rotation of crops with different cultural practices, occasional scavenging of deep moisture and nutrients with a deep-rooted crop, and reduction of erosion with sod Rotating cereals with legumes is recommended for reducing *Striga* infestations in small farmer agriculture (Doggett, 1984). Best control occurs when previous fallow and crop residues are burnt prior to land preparation or incorporated with soil. In case farmers use herbicide, crop rotation can help them also to rotate their herbicides, thus ensuring that weeds resistant to a given herbicide do not take over in the fields. But although crop rotation can play role in reducing weed infestation constraints, this cultural weed management should be done in conjunction with other methods of weed control (Akobundu, 1987). But systematic crop rotation is not common in the agriculture of the humid and sub humid tropics. Limited crop rotation may be found in the inland valleys and other lowlands of West Africa with available irrigation water during the dry season. Even with a supplemental irrigation scheme as an artesian well at Vovokame (Benin), more lucrative rice-vegetable rotation was replaced by less lucrative rice-sweet corn rotation due to the waterlogging of the vegetable crops during the dry season and the non-intervention of the farmers to improve the situation. Because in the parts of the lowland which were too wet for vegetables in the dry season, open drainage channels could have been dug to reduce waterlogging. During the rainy season, the ends of the same channels might be blocked to reduce drainage and, if necessary, to raise water levels for flood irrigation of rice fields and suppression of weeds. Trade-offs are always involved in crop rotation, since income may be reduced and weeds and disease may increase with the intensification linked to rotation (Beets, 1990). Successful rotations are those that offer, on balance, more benefits to income and constraints reduction than they cost.

As crop rotation involves rice-vegetables in inland valleys, postharvest facilities for drying, threshing, milling, storage and transport should be included in inland valley development schemes (Wopereis et al., 2013). Emphasis should be placed on leafy legumes and fruits vegetables (consumed fresh) which have very short shelf-life.

Assuming it will prove possible to grow more crops and obtain better yields in the inland valleys, socio-economic and institutional aspects determine whether or not, farmers will find it profitable and feasible too.

The first socio-economic and institutional aspect revolves around the commercialization issues. Most smallholder farmers grow crops mainly for subsistence and a small surplus is for sale. In the past, these surpluses were used for self-sufficiency at village level or at regional or provincial level. But since the start of widespread urbanization, inter-regional trade, and the nationalization of economies, these surpluses are increasingly being used to feed urban populations.

The second socio-economic and institutional aspect deals with the access to markets, inputs and credits. Regarding this aspect, generally most developed inland valleys in West Africa are near waterways and relatively accessible areas. Thus, trade has been an important feature of the system. At the periphery of extensive commercialized systems, however, localized, discrete, and self-sufficient marketing systems have remained (Bray, 1986). Because rice is easily stored and transported; access to markets is not usually a problem. Access to production inputs and credit requires more organization. Traditionally, trade is controlled by landlords and middlemen (primary and secondary collectors, wholesalers and retailers), and inputs and credit are channelled through them. Sometimes, middlemen also control rice mills.

The third socio-economic and institutional aspect is related to labour. For the smallholder farming systems in the developing countries, lowland rice cultivation requires high labour inputs that vary between 80 to 200 man/days per ha (Stessens, 2002). The most labour intensive and critical operations are land preparation (tillage and levelling), planting, weeding, and sometimes harvesting. Activities for these operations invariably create labour peaks and constraints. In case there is shortage of family labour, occasional labour is hired, or use is made of communal (village) labour. Operations such as weeding are not done at the correct juncture or are not done at all. On the whole, labour demands are unevenly distributed over time, and labour input per ha has tended to increase as farm size decreases since all operations, particularly land preparation become less efficient (Stessens, 2002). Nowadays, modernization has sometimes replaced pure manual labour. In some areas, harvesting is done now with sickle, whereas before hand-knives were used to harvest.

The fourth socio-economic and institutional aspect dealing with lowland rice based systems is linked to the farm size and ownership. Many different forms of sizes, ownership and tenancy are found in lowland smallholder systems. In northern Cote d'Ivoire, farm sizes are relatively large (from a quarter to 5 ha), whereas in Benin, the farm sizes are very small (from 0.01 to 0.2 ha), may be due to population pressure. And ownership patterns have had different effects on the character of production and productivity. In most cases, landlords have prevented tenants from modernizing and developing the lowland, and in few case landlords have initiated change. In case of introduction of innovations, landlords and large farm owners were the leading farmers in adoption, since those innovations made farming profitable. But other studies indicate that, although small farmers and tenants may initially lag behind in adopting new technology, they eventually may use it more than large owner-farmers (Hossain and Fischer, 1995).

The fifth socio-economic and institutional aspect concerning lowland rice cultivation in West Africa concerns the decision making process and gender issue. According to (Beets, 1990), decision-making in subsistence oriented lowland rice cropping systems in developing countries, is complex process which involves a large number of factors. Apart from the sociological and psychological factors, there are many physical and economic considerations involved in way a smallholder makes his decision. In many traditional societies, farming is done by an extended family, under the direction of the head (generally male), giving the main decision making power to the older people (Gastellu, 1980). In those societies, most of the lowland agricultural work (planting, weeding and harvesting) is done by women, but often they are not involved in decision making. This often leads agricultural extension efforts on innovations to address the wrong audience. In general in those lowlands, although women perform most of the tedious tasks, men control access to the fertilizers and other inputs needed to obtain the best yields. In households with a married couple, fertilizer is sometimes applied to food crops, but only once the needs of the cash crops have been met. Households consisting of women farming by themselves seldom use any inputs at all. Also in the smallholder lowland rice systems, when a farm enterprise managed by women shows signs of becoming profitable, their husbands or other men in the neighbourhood usually try to take it over. Thus making lowland rice production worthwhile runs serious risks of depriving women of their plots, especially in areas where land tenure is not secure.

The sixth and final aspect concerning lowland rice based systems development concerns the organization of the social structures and institutions. The lowland rice based farming system can often be productive and successful with irrigation. This requires a well-organized, disciplined society since irrigation systems are almost always communally owned and operated (tube wells are sometimes the exception). For Beets (1990), the smallholder can be seen as an independent management unit controlling on-farm activities but, at the same time, he is inextricably linked into much larger-scale co-operative or communal units for the macro-management of all-important water. The paradox between the individual and the communal nature of lowland rice cultivation has been very important in the history of the smallholder lowland rice based systems.

6.5. General conclusion

The studies in Benin and Cote d'Ivoire have identified major problem weeds along catena of inland valleys typically found in the southern Guinea Savanna zone. The differences in weed community compositions were explained largely by the hydrological gradient along the heterogeneous catena. Most of those weeds were annuals and had high ecological plasticity growing under a range of different hydrological conditions, ranging from freely draining uplands on the valley crests to the saturated and temporarily flooded valley bottoms. Weed management in inland valleys should prioritize these species with a large ecological plasticity and pay attention to these species as they may become more dominant or are more difficult to control in this ecology where flooding cannot, or only partially, be controlled. Some weeds were auxiliary and useful; suggesting that weed control methods which require chemical technology in eradicating all types of weeds might not be acceptable to farmers in intensified cropping systems, as long as no other sources of wild vegetables are available. In Benin, hand weeding remained the major means to control weeds. Herbicides uses were limited because of the expense and limited cash. No significant differences were found between the different weed control practices along the heterogeneous catena positions. Within a site, the primary determinants of the weed control method used were the financial and labour resources of the farmers. Better water management in an inland valley of Cote d'Ivoire through the installation of field bunds increased yields and lowered weed biomass.

Looking ahead for good agronomic practices in inland valleys

Generally under low population pressure, new crops and techniques are being introduced at a rather slow pace, and adjustments to the environment come about more or less naturally, after a period of small scale trial and error. So the dynamic of the farming system is like a gradual evolution. In such a context, farming systems have a chance of being more or less in accordance with ecological site characteristics without endangering the environment. Some authors even speak of a system in equilibrium or a sustainable system. In West African inland valleys, rice is cropped in alternation with short fallow periods (sometimes in rotation with vegetables) with apparent success because most of the rice is intended to be sold. Moisture is available during most of the year or can be supplemented by irrigation, and this allows for flexible planting and harvesting time. Due to demographic pressure in most inland valleys of West Africa, poor land management and failure to adjust the systems to local resources brings about a more or less general collapse of the equilibrium of the rice-based systems. In this situation, the ecological influences may be far greater than one or two extra rotations, and the strategies of developing the inland valleys will encompass agro-technical aspects and the socio-economic of inland valley rice-based systems. Adoption of agro-technical aspects will be related to the nature of the technologies. Although bunds improve water control, they still do not create the uniform conditions needed to ensure the fertilizer-seed-weed control performs equally well in all parts of the toposequence. The solution would be to control better water, and this could be achieved by building a relatively cheap small concrete dam with a wooden sluice, feeding irrigation channels that would convey water to farmers' fields by gravity. This is a more expensive intervention for farmers' standard that would require them to pool their resources through some farmers' organizations or multi stake holder platform (MSP), or request partners such as projects and NGO's.

Selected mechanization (rotary weeders, power tillers, threshers…) can be important development intervention, particularly to unlock development blocks in lowland rice-based systems. Ultimately, this up scaling of inland valleys development will lead to the '*Sawah* Ecotechnology' for improving rice growing environment in farmers' fields by means of bunding, leveling, puddling, etc. being associated with small-scale irrigation scheme to increase rice productivity (Figure 51).

Figure 51. *Sawah* in an inland valley in Ghana.

However, during the past four decades the up scaling of inland valleys development has been over-emphasized and there is a history of trying to promote inappropriate technology, particularly tractors which are too sophisticated, too large, and too difficult to maintain. The future of the intervention seems to lie in developing more location-specific appropriate technology; introducing and improving animal draught power, and machines that are (partly) locally made and can be locally maintained (Beets, 1990).

Finally if inland valley lowland rice based systems is diversifying from rice in favor of fruits and vegetables, there is a need for good market for quick disposal or good network of processing. Failing that, the diversification would be limited. Frequently overlooked in the diversification debate is the importance of efficient marketing systems and the associated processing and storage functions that must be carried out to provide an outlet for farmers to sell agricultural commodities other than rice.

Many aspects of inland valley agricultural development and sustainability are compatible with current farming practices and could become more accessible to farmers if government policies are restructured to reflect the true environmental costs of agricultural production.

But ecological changes brought about by the development of some inland valleys, can lead to the chaos phase with the propagation of water-borne diseases that can hinder farmers' practices (mainly manual weeding), unless protective mosquito nets and plastic boots are available and affordable to farmers against some of those diseases. These diseases are malaria, schistosomiasis (bilharzia), trypanosomiasis (sleeping sickness), onchocerciasis (river blindness), dracontiasis (guinea worm) and leech (*Hirudo medicinalis*) (Figure 52). The distribution and incidence of water-borne are influenced not only by water management for agricultural production but also by the quality of community water supplies, sanitation and housing facilities, and by the degree of settlement and migration of the population. Improvements in drinking water supplies, in excreta disposal, and in nutrition and nutritional hygiene can reduce the transmission of many infections (Windmeijer and Andriesse, 1993). Therefore, from the beginning of the development of inland valleys, one has to incorporate environmental safeguards to fight these diseases (Oomen et al., 1990) .

Figure 52. Leech (*Hirudo medicinalis*) displayed by inland valley farmers at Vovokame (Benin).

As the cultivation of inland valley rice-based cropping systems is becoming important in sub humid savanna and in the humid forest zones of large parts of West Africa, the suitability of other upland staple crops (during the dry season) for diversification in the inland valley rice-based cropping systems should be tested. The more productive and sustainable use of inland valley rice-based cropping systems may confine demand for land, thus delaying the breakdown of the traditional shifting cultivation system, and contributing to the ecological preservation of the remaining tropical savannas and forests.

Appendix A. List of weeds inventoried in the survey in Benin.

Family	Genus and species	Eppo code	Biological form	Photosynthetic pathway
Monocotyledoneae				
Commelinaceae	*Commelina benghalensis* L.	Comm ben	Hem	C_3
	Commelina diffusa Burm. f.	Comm dif	Hem	C_3
	Commelina erecta L.	Comm ere	Hem	C_3
Cyperaceae	*Cyperus difformis* L.	Cype dif	T	
	Cyperus distans L.	Cype dis	G	
	Cyperus haspan L.	Cype has	G	C_3
	Cyperus iria L.	Cype iri	T	C_4
	Cyperus sphacelatus Rottb.	Cype sph	T	
	Cyperus esculentus L.	Cype esc	G	C_4
	Cyperus longibracteatus Cherm.	Cype lon	T	
	Cyperus rotundus L.	Cype rot	G	C_4
	Cyperus tuberosus Rottb.	Cype tub	G	
	Fimbristylis ferruginea (L.) Vahl	Fimb fer	G	C_4
	Fimbristylis littoralis Gaudich.	Fimb lit	T	C_4
	Kyllinga erecta Schum.	Kyll ere	G	C_4
	Mariscus cylindristachyus Steudel	Mari alt	G	C_3
Gramineae	*Brachiaria deflexa* (Schum.) C.E. Hubb. Ex. Robyns	Brac def	T	C_4
	Brachiaria spp.	Brac spp	T	C_4
	Brachiaria villosa (Lamarck) A. Camus	Brac vil	T	C_4
	Chloris pilosa Schum.	Chlo pil	T	C_4
	Dactyloctenium aegyptium (L.) P. Beauv.	Dact aeg	T	C_4
	Digitaria horizontalis Willd.	Digi hor	T	C_4
	Echinochloa colona (L.) link.	Echi col	Hem	C_4
	Echinochloa obtusiflora Stapf	Echi obt	T	C_4
	Eleusine indica (L.) Gaertner	Eleu ind	T	C_4
	Eragrostis tenella (L.) Roemer & Schultes	Erag ten	T	C_4
	Imperata cylindrica (L.) P. Beauv.	Impe cyl	G	C_4
	Leersia hexandra Sw.	Leer hex	G	C_3
	Leptochloa caerulescens Steudel	Lept cae	T	C_4
	Panicum laxum Sw.	Pani lax	T	C_4
	Paspalum scrobiculatum L.	Pasp scr	Hem	C_4
	Rottboellia cochinchinensis (Lour.) W. Clayton	Rott coc	T	C_4
	Setaria pumila (Poiret) Roemer & Schultes	Seta pum	T	C_4
	Sorghum arundinaceum (Desv.) Stapf	Sorg aru	T	C_4

Appendix A (Continued)

Family	Genus and species	Code	Biological form	Photosynthetic pathway
Dicotyledoneae				
Amaranthaceae	*Alternanthera sessilis* (L.) R. Br. Ex Roth	Alte ses	Hem	C_3
	Amaranthus spinosus L.	Amar spi	T	C_4
	Amaranthus viridis L.	Amar vir	T	C_4
	Celosia trigyna L.	Celo tri	T	C_4
	Gomphrena celosioides Mart.	Gomp cel	T	C_4
Capparidaceae	*Cleome ciliata* Schum. & Thonn.	Cleo cil	T	C_3
	Cleome viscosa L.	Cleo vis	T	C_3
Convolvulaceae	*Ipomoea aquatica* Forssk.	Ipom aqu	Hel	C_3
	Ipomoea involucrata P. Beauv.	Ipom inv	T	C_3
Asteraceae	*Acanthospermun hispidum* DC	Acan his	T	
	Ageratum conyzoides L.	Ager con	T	C_3
	Aspilia africana (Pers.) C. Adams	Aspi afr	T	C_3
	Blumea aurita (Linn. f.) DC	Blum aur	T	
	Crassocephalum crepidioides (Benth) S. Moore	Cras cre	T	
	Eclipta prostrata (L.) L.	Ecli pro	T	C_3
	Emilia praetermissa Milne-Redhead	Emil pra	T	C_3
	Enhydra fluctuans Lour.	Enhy flu	T	C_3
	Struchium sparganophora (L.) Kuntze	Stru spa	T	C_3
	Synedrella nodiflora Gaertner	Syne nod	T	C_3
	Tridax procumbens L.	Trid pro	T	C_3
	Vernonia cinerea (Linn.) Less.	Vern cin	T	
Euphorbiaceae	*Croton lobatus* L.	Crot lob	T	
	Euphorbia heterophylla L.	Euph het	T	C_4
	Euphorbia hirta L.	Euph hir	T	C_4
	Euphorbia hyssopifolia L.	Euph hys	T	C_4
	Mallotus oppositifolius (Geisel.) Muell. Arg.	Mall opp	P	
	Phyllanthus amarus Schum. & Thonn.	Phyl ama	T	
	Securinega virosa (Rox. Ex Willd.) Bail	Secu vir	P	
Hydrophyllaceae	*Hydrolea glabra* Schum. & Thonn.	Hydr gla	T	
Labiatae	*Basilicum polystachyon* (L.) Moench	Basi pol	T	
Lamiaceae	*Solenostemon monostachyus* (P. Beauv.) Brig.	Sole mon	T	
Logoniaceae	*Spigelia anthelmia* L.	Spig ant	T	

Appendix A (Continued)

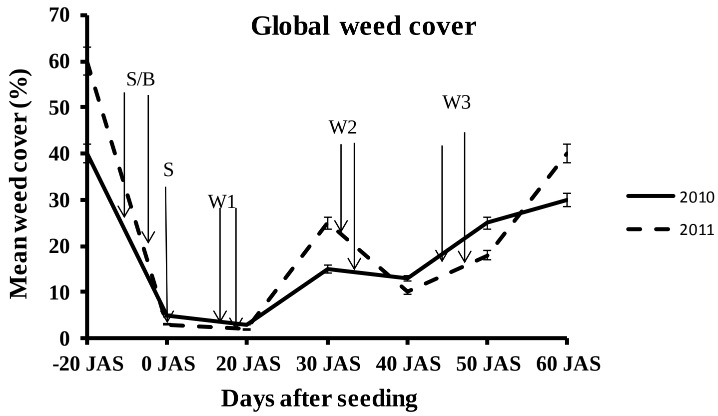
Family	Genus and species	Code	Biological form	Photosynthetic pathway
Dicotyledoneae				
Lythraceae	*Ammannia baccifera* L.	Amma bac	T	
	Ammannia prieureana Guill. & Perr.	Amma pri	T	
Molluginaceae	*Mollugo nudicaulis* Lam.	Moll nud	T	
Nyctaginaceae	*Boerhavia erecta* L.	Boer ere	T	C_4
Onagraceae	*Ludwigia abyssinica* A. Rich.	Ludw aby	T	
	Ludwigia deccurens Walt.	Ludw dec	T	
	Ludwigia hyssopifolia (G. Don)Exell	Ludw hys	T	
	Ludwigia octovalvis (Jacq.) Raven	Ludw oct	Hel	
Papilionaceae	*Aeschynomene indica* L.	Aesc ind	T	C_3
	Centrosema pubescens Benth.	Cent pub	T	
	Indigofera hirsuta L.	Indi hir	T	
Pontederiaceae	*Heteranthera callifolia* Rchb. Ex Kunth	Hete cal	T	
Piperaceae	*Peperomia pellucida* (L.) H. B. & K.	Pepe pel	T	
Portulacaceae	*Portulaca quadrifida* L.	Port qua	T	C_4
	Portulaca oleracea L.	Port ole	T	C_4
	Talinum triangulare (Jacq.) Willd.	Tali tri	T	
Rubiaceae	*Oldenlandia corymbosa* L.	Olde cor	T	
	Oldenlandia herbacea (L.) Roxb.	Olde her	T	
	Pentodon pentandrus (Schum. & Thonn.) Vatke	Pent pen	T	
	Spermacoce ocymoides Burm. f.	Sper ocy	T	
Scrophulariaceae	*Bacopa decumbens* (Fernald) F. N. Williams	Baco dec	T	
	Scoparia dulcis L.	Scop dul	T	
Solanaceae	*Physalis angulata* L.	Phys ang	T	
Sphenocleaceae	*Sphenoclea zeylanica* Gaertner	Sphe zey	T	
Sterculiaceae	*Melochia corchorifolia* L.	Melo cor	P	

Appendix A (Continued)

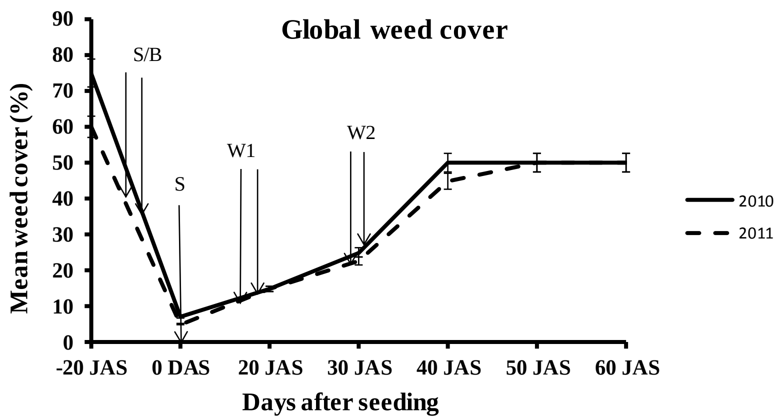
Family	Genus and species	Code	Biological form	Photosynthetic pathway
Dicotyledoneae				
Tiliaceae	*Corchorus aestuans* L.	Corc aes	T	
	Corchorus olitorius L.	Corc oli	T	
Verbenaceae	*Stachytarpheta indica* (Linnn.) Vahl	Stac ind	P	
Pteridophyte				
Thelypteridaceae	*Cyclosurus striatus* (Schum.) Ching	Cycl str	Hel	

Biological life forms: G = geophytes ; Hem = hemicryptophytes; Hel = helophytes; P = phanerophytes; T = therophytes

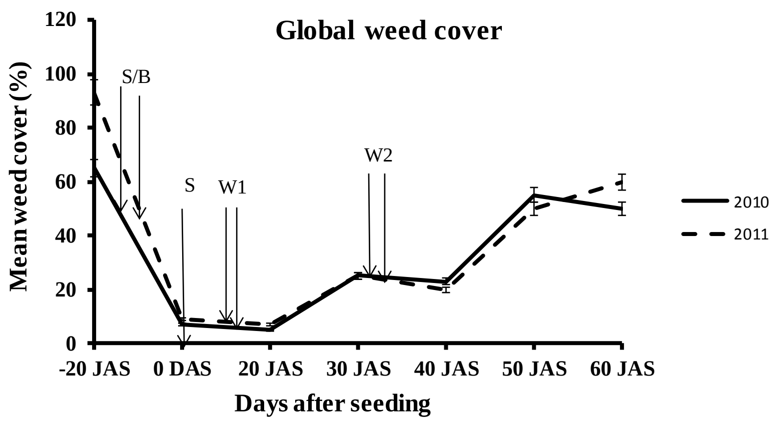
Appendix B. Global weed cover for selected dry season farmers.



Farmer AA weeding manually jute mallow at Agbedranfo.

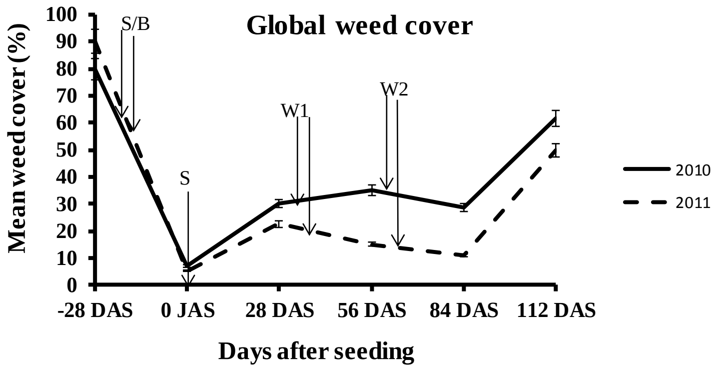


Farmer FT weeding manually jute mallow at Agbedranfo.

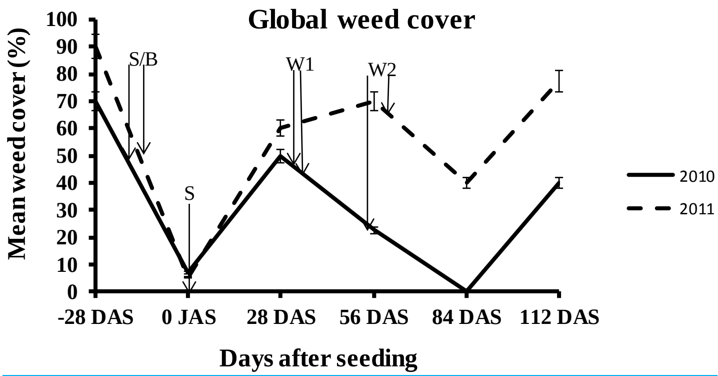


Farmer TY weeding manually jute mallow at Agbedranfo. (S/B= slash/burn; S = seeding; W1=first weeding; W2= second weeding).

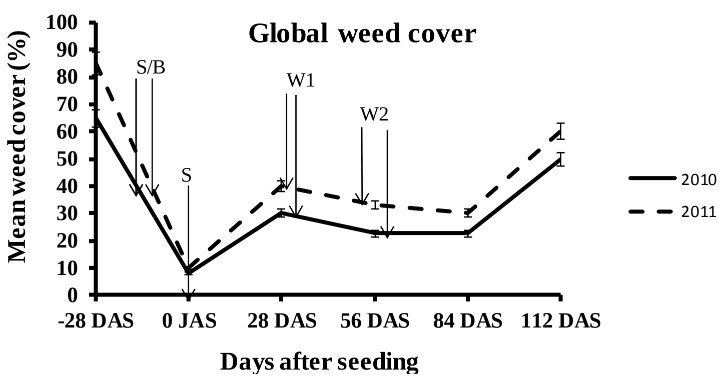
Appendix C. Global weed cover for selected rainy season farmers.



Farmer AD weeding manually rice at Agbedranfo.

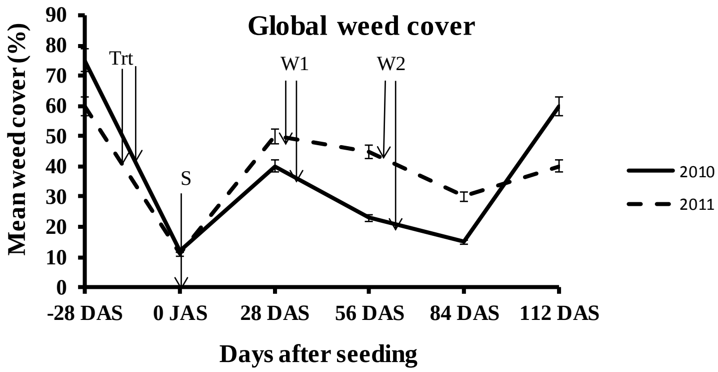


Farmer AK weeding manually rice at Agbedranfo.

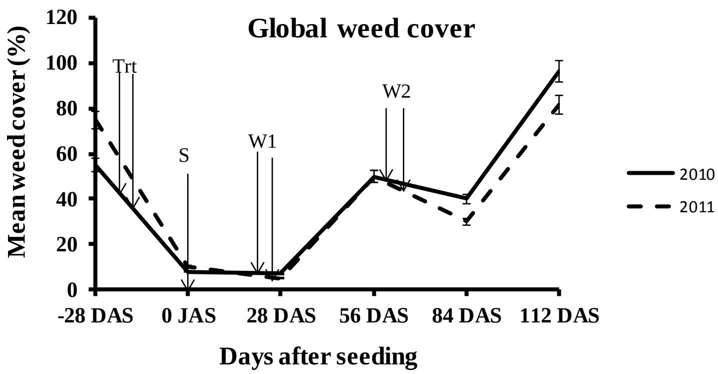


Farmer GV weeding manually rice at Agbedranfo. (S/B= slash/burn; S = seeding; W1=first weeding; W2= second weeding).

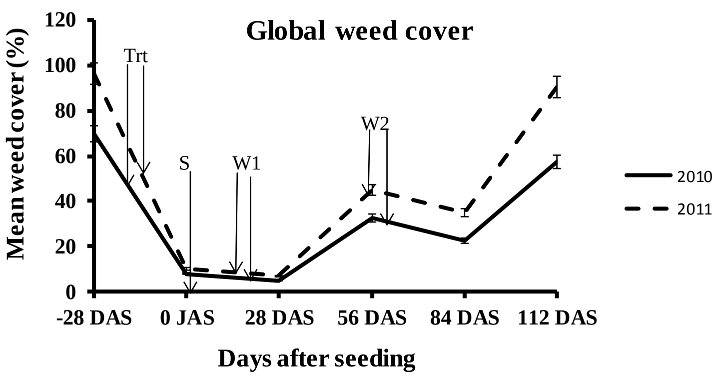
Appendix C (Continued)



Farmer AA using total herbicide for land preparation and weeding manually rice at Houinga.



Farmer DF using total herbicide for land preparation and weeding manually rice at Houinga.



Farmer GC using total herbicide for land preparation and weeding manually rice at Houinga. (Trt= total herbicide; S = seeding; W1=first weeding; W2= second weeding)

Appendix D. Description and management of major common weeds found in inland valleys of Benin and Cote d'Ivoire.

1. *Ageratum conyzoides*

Family	Asteraceae
Weed Type	Broadleaf
Global Description	Terrestrial, annual, erect herb, up to 120 cm tall. Taproot white or brown. Stem rounded, solid, hairy. Stipules absent. Leaves simple, not divided or lobed, opposite, stalked, ovate, hairy or not on both sides, margin coarsely dentate, apex acute, base rounded or truncate, pinnately veined. Flowers bisexual, grouped together in a terminal head, consisting of tubular flowers only, sessile, white or blue, petals 5. Fruit an achene, pappus present. The species has great morphological variation, and appears highly adaptable to different ecological conditions.
General Habit	An erect, herbaceous annual plant, 30 to 80 cm tall.
Stem	Stems are covered with fine white hairs, stem is often red.
Leaf	Leaves are opposite, pubescent with long petioles and include glandular trichomes, leaves covered with fine hair, ovate, to 3 inches long by 2inches wide, more or less pointed apex, margin regularly serrated, with blunt teeth.
Inflorescence	Terminal, contains 30 to 50 pink flowers arranged as a corymb and are self-incompatible.
Flower	The flowers are hermaphrodite and are pollinated by insects, individual flower heads are ¼ inch across with large numbers of tubular flowers surrounded by 2 or 3 rows of narrow pointed bracts with membranous margins.
Fruit	A slender achene encircled with 5 white pointed scales, black in colour.
Seed	Seeds are positively photoblastic, and viability is often lost within 12 months, the dark seeds have scales and ends in a needle-like shape.
Biology	Reproduction by seeds. Seeds are dispersed by wind and water. Flowering all the year round and may produce up to 40 000 seeds per plant.
Ecology	The species is widespread in moist uplands, hydromorphic and temporary, shallow flooded lands. The plant prefers light (sandy), medium (loamy) and heavy (clay) soils, acid, neutral and alkaline soils.

Origin	Central and South America (Wagner et al., 1999; p. 255), now a worldwide weed.
World Distribution	Tropical and subtropical area, Africa, Indian continent, S.E. Asia, Malaysia, Central and South America.
Global Weediness	May become troublesome in plantations after grasses have been suppressed. The relative tolerance to flooding, abundant seed production and rapid germination of this species makes it a successful weed in **rain-fed rice cropping systems in Africa**.
Local weediness	**Benin**: Frequent but not abundant. Burkina Faso: Frequent but not abundant. Chad: Rare and not abundant. **Cote d'Ivoire**: Frequent and usually abundant. Ghana: Frequent and usually abundant. Kenya: Frequent but not abundant. Mali: Frequent but not abundant. Nigeria: Rare but abundant when present. Senegal: Rare but abundant when present. Tanzania: Frequent and usually abundant. Uganda: Frequent and usually abundant.
Global control	Ageratum conyzoides can be readily controlled when young by hand pulling or hoeing. Seedlings and young stages readily controlled by 2,4-D, MCPA and other growth regulators that are used on cereal crops.
Uses	A. conyzoides has been reported to have medicinal and bioherbicidal applications (Xuan et al., 2004). Such uses however are not widespread. The leaves and the flowers yield 0.2% essential oil with a powerful nauseating odour. The oil contains 5% eugenol, which has a pleasant odour. The oil from plants growing in Africa has an agreeable odour, consisting almost entirely of eugenol. In Brazil A. conyzoides is used as an infusion is prepared with the leaves or the entire plant and employed to treat colic, colds and fevers, diarrhea, rheumatism, spasms, and as a tonic. It is also highly recommended there for burns and wounds. In other countries in Latin and South America the plant is widely used for its antibacterial properties for numerous infectious conditions and bacterial infections. In Africa, ageratum is used to treat fever, rheumatism, headache, pneumonia, wounds, burns and colic. A decoction of the fresh plant is used as a hair wash, leaving the hair soft, fragrant and dandruff free. Also leaves are applied to cuts, burns and sores (styptic) and externally for body rash. They are also used against sore throat, spasms, diarrhea and epilepsy. The phytochemicals in tropical whiteweed include alkaloids (pyrrolizidine alkaloids lycopsamine and echinatine), cumarins, essential oils, flavonoids and tannins. It shows promising results for anti-inflammatory and antioxidant activity due to the flavonoid fraction. The plant contains between 0.7 - 2.0% essential oil, plus alkaloids and saponins. The whole plant is anti-inflammatory and anti-allergic. The juice of the fresh plant, or an extract of the dried plant, is used in the treatment of allergic rhinitis and sinusitis. The juice of the fresh plant is also useful in treating post-partum uterine hemorrhage. The juice of the root is

	antilithic. A paste of the root, mixed with the bark of *Schinus wallichii*, is applied to set dislocated bones.
Reference	Xuan, T.D., Shinkichi, T., Hong, N.H., Khanh, T.D., and Min, C.I. (2004). Assessment of phytotoxic action of *Ageratum conyzoides* L. (Billy goat weed) on weeds. *Crop Protection* **23**, 915-922.

Ageratum conyzoides

Source:http://www.afroweeds.org/network/pg/file/read/general-guidelines-for-weed-management-in-lowland-rice

2. *Cyperus difformis*	
Family	Cyperaceae
Weed Type	Sedge
Global Description	Erect annual tufted plant of 50 cm high, roots fibrous, stem triquetrous, solid, glabrous.
General Habit	A tufted plant up to 50 cm high.
Underground System	Fibrous and reddish, without tubers, bulbs or rhizomes.
Stem	Are smooth, triquetrous, slightly winged.
Leaf	Smooth (or slightly scabrid on the midrib and margin), flat, linear, 5-25 cm long or often two-thirds of the plant height, 2-6 mm wide, usually 3 spreading leaf-like bracts.
Inflorescence	Consists of dense, globose, umbellate heads, simple or compound, 5-15 mm in diameter, with 10-60 stellately spreading spikelets, subtended by 1-4 leaf-like bracts, one of which can be up to 25 cm long. The main umbel has 6-12 rays long of 3 to 5 cm.
Flower	Spikelets are linear to oblong-linear, compressed but slightly swollen, obtuse, 3-5 mm long, 0.8-1.25 mm wide, 6-30 flowered. Glumes are 0.6-0.8 mm long, obovate, pale-yellowish to dark reddish-brown with yellow or white margins and a green midrib ending in a short mucro.
Fruit	Achenes are 0.6-0.8 mm long and 0.3-0.4 mm wide, triangular, obovate-elliptic, yellowish-brown or pale-brown, minutely papillose.
Biology	An annual tufted plant propagates by seeds.
Ecology	Plant normally grows in flooded or in very moist soils. It is primarily a weed of paddy or flooded rice. It is frequently found in small pools, along rivers, canals and streams, in open wet places and in grassy swamps. It grows best in rich, fertile soils but can grow in poor sandy or clay soils of unused lands or in fallow rice fields.
Origin	Native of the old world tropics.
World Distribution	Now widespread throughout southern Europe, Asia, Central America, North America, **Africa** and the islands of the Indian and Pacific (Holm et al., 1977)
Global Weediness	Can be particularly abundant where fields are only intermittently flooded or where land leveling is poor. The weed is well adapted to direct-seeded rice production methods (Johnson, 1997; Rao et al., 2007). Infestations can build up rapidly because the plant produces large quantities of seed, which can germinate at any time of the year, and it completes its cycle in

	6-8 weeks, so that several generations can grow in one year (Iven, 1989).
Local weediness	Benin: Frequent and usually abundant. Burkina Faso: Frequent and usually abundant. Chad: Frequent and usually abundant. Cote d'Ivoire: Frequent and usually abundant. Ghana: Frequent and usually abundant. Kenya: Frequent but not abundant. Mali: Frequent and usually abundant. Nigeria: Frequent and usually abundant. Senegal: Frequent and usually abundant. Tanzania: Frequent and usually abundant. Uganda: Frequent and usually abundant.
Global control	Cultural control: hand and mechanical weeding in row-planted rice plants can provide effective control. Chemical control: Bentazon, butachlor, 2,4-D, MCPA, pretilachlor, propanil, and thiobencarb reported to be effective. Because of its back of underground perennating organs C. difformis is easier to control than species as C. rotundus and C. esculentus. As a post-weed-emergence treatment may be used in transplanted rice. Pre-weed-emergence chemicals are also available for use in rice butachlor and oxidiazon, both of which are available as mixtures with propanil.
Reference	Ivens, G.W. (1989). Eastern Africa weeds control. Oxford University press, Nairobi. 20p; Holm, L.G., Plucknett, D.L., Pancho, J. V., and Herberger, J.P. (1977). The world's worst weeds: distribution and biology. Honolulu Hawaii (USA): The University of Hawaii Press. 609 p; Johnson, D.E. (1997). Weeds of rice in West Africa. WARDA, Bouaké. 74p; Rao, A.N., Johnson, D.E., Sivaprasad, B., Ladha, J.K., and Mortimer, A.M. (2007). Weed management in direct-seeded rice. *Advances in Agronomy* **93**, 153–255.



Cyperus difformis

Source:http://www.afroweeds.org/network/pg/file/read/general-guidelines-for-weed-management-in-lowland-rice

3. *Echinochloa colona*

Family	Poaceae
Weed Type	Grass
Global Description	Annual grass. Tufted, erect and jointed, often flat on the ground, 30-75 cm high. Reddish-purple or green. Leaves linear to10-15 cm long. Seed head is a panicle with 3-10 branches 5-15 cm long. Propagates by seeds.
General Habit	A tufted annual grass, up to 75 cm tall.
Underground System	Rooting at nodes. Root fibrous, white or brown.
Stem	Usually grow outwards at the base before turning upwards and are often purple near the base.
Leaf	Glabrous, up to 25cm long and 3-8 mm wide, sometimes banded with purple and ligule absent.
Inflorescence	In raceme of 8-10 short, densely crowded spikes at the top of the stem.
Flower	The spikes making up the inflorescence are up 3 cm long and 3-4 mm wide, usually about half their length a part on the main stem, which they join at acute angle. They are made up of numerous almost stalkless spikelets arranged in four distinct rows. Individual spikelets are 2-3 cm long, oval in shape with a pointed tip (but not extended into an awn as in the related E. crus-galli) and contain a single fertile floret.
Seed	Seed head is a panicle with 3-10 branches 5-15 cm long.
Biology	This species propagates mostly by seeds but also vegetatively; one jungle rice plant can produce 3000 to 6000 seeds. It germinates during the rainy season or when water levels are on the rise and dies out during the dry season. The flowering starts 3 or 4 weeks after germination, quickly followed by fructification and the first seeds come to maturity 45 days later.
Ecology	A C_4 annual species which is adapted to full sunlight or partial shade and grows on loam, silt and clay soils. It grows in drains, low-lying grasslands, farmlands, in both dry and marshy places. This species is one of the most important weeds of upland rice under moist conditions. It occurs most commonly at low altitudes but can extend up to about 2000m.
Origin	Tropics and subtropics.
World Distribution	It is widely distributed in tropics and subtropics, including South and Southeast Asia and **tropical Africa (common in moist upland, hydromorphic and poorly flooded, lowland rice)**.

Global Weediness	An important crop weed throughout the tropics and subtropics and has become one of the world's most serious grass weeds (Holm et al, 1991). It is an important weed not only of rice crop but also sugarcane, cotton, maize, etc. It is mostly present at the middle and at the end of cultural cycle. Because it resembles rice in the seedling stage it is sometimes transplanted into the fields with the crop. This weed is an excellent competitor and if rice culture is badly managed the crop may be forced out by increasing numbers of this weedy plant. This weed is also an alternate host of diseases, insects, and nematodes (Holm et al., 1991).
Local weediness	**Benin**: Frequent and usually abundant. Burkina Faso: Frequent and usually abundant. **Cote d'Ivoire**: Frequent and usually abundant. Mali: Frequent and usually abundant. Chad: Rare but abundant when present. Ghana: Frequent and usually abundant. Senegal: Frequent and usually abundant. Nigeria: Frequent and usually abundant. Tanzania: Frequent and usually abundant. Uganda: Frequent and usually abundant.
Global control	Cultural control: cultivation during early growth can control the weed. Manual control is difficult in the early stages. Biological control: In Japan, the pathogen *Exserohilum monoceras* is being evaluated as a bioherbicide for control of Echinochloa species in rice. In the Philippines, E. monoceras killed seedlings of E. colona but did not affect rice. Chemical control: E. colona can be controlled by pre-emergence application of butachlor at 1.5 kg a.i/ha, Anilophos at 400 g/ha, Pretilachlor at 1.0 kg/ha, Pendimethalin at 1.5 kg/ha.
Uses	Often used in times of food shortage as a famine food. In Chad (central) and Sudan (Kordofan, Darfur) the seeds of this plant are ground into flour from which porridge or bread can be prepared. In Rajasthan in India the seeds are used as rice - hence its English common name of 'jungle rice', from the Hindustani jangal, meaning wild. Indian barnyard millet (*Echinochloa frumentacea*), a cultivated crop in India, was domesticated from *E. colona*.
Reference	Holm, L.G., Plucknett, D.L., Pancho, J. V., and Herberger, J.P. (1977). The world's worst weeds: distribution and biology. Honolulu Hawaii (USA): The University of Hawaii Press. 609 p

Echinochloa colona

Source:http://www.afroweeds.org/network/pg/file/read/general-guidelines-for-weed-management-in-lowland-rice

4. *Hydrolea glabra*	
Family	Hydrophyllaceae
Weed Type	Broadleaf
Global Description	An erect annual broadleaf herb, about 75 cm high. The stem is thick and spongy, completely hairless. The leaves are alternate, simple, narrow, long, subsessile. They are regularly arranged throughout the stem. The flowers are blue. They are clustered in the axils of leaves along the stem or in cymes on long stalk sat the top of the plant.
Underground System	Tap-root.
Stem	The stem is erect, cylindrical, smooth and spongy of about 30-75 cm height.
Leaf	Alternate, lanceolate, to 4-8cm long, 1-1.5 cm wide, margins entire, blade sharply pointed at apex, slimy and smooth on both surfaces.
Inflorescence	Axillary raceme, often clustered along stem.
Flower	Blue with calyx tubes to 6mm long.
Fruit	Capsule, smooth, broadly ovoid, splitting vertically when ripe.
Biology	It reproduces from seeds or stolons.
Ecology	Lowland rice, pools, drains and swamp.
Local weediness	Benin: Frequent but not abundant. Burkina Faso: Rare but abundant when present Cote d'Ivoire: Frequent but not abundant. Ghana: Frequent and usually abundant. Mali: Rare but abundant when present Nigeria: Rare but abundant when present Senegal: Rare and not abundant.
Uses	Yoruba doctors use the plant in a treatment to develop intelligence, hence òyé: Yoruba for 'intelligence', is compounded in the Yoruba name for the plant (see above) In Sierra Leone Mendes grind up the leaves to rub on babies suffering headache Ijo of SE Nigeria make unspecified medicinal use of the plant .

Hydrolea glabra

Source:http://www.afroweeds.org/network/pg/file/read/general-guidelines-for-weed-management-in-lowland-rice

5. *Ludwigia hyssopifolia*	
Family	Onagraceae
Weed Type	Broadleaf
Global Description	Terrestrial, annual or perennial, broadleaved, erect herb, up to 150 cm tall. Taproot white or brown. Stem rounded or ribbed, glabrous. Stipules present, triangular. Leaves simple, not lobed or divided, alternate, spiral, stalked, lanceolate or elliptic, more than 2 cm long/wide, glabrous on both sides, margin entire, apex acute, base acute or attenuate, pinnately veined. Flowers bisexual, solitary, axillary, sessile, petals 4, yellow. Fruit a capsule, indehiscent or opening in irregular pieces.
Underground System	Taproot white or brown.
Stem	Is multi-branched, my appear 3 or 4-angled, green but may have reddish or purplish coloration marked with striations and slightly winged.
Leaf	Leave are alternate, rather variation in size, lanceolate to linear lanceolate, narrowly cuneate at the base, acute to acuminate to the tip, about 2-10 cm long and up to 1.5 cm wide. They are usually stalkless or are sometimes very shortly stalked.
Inflorescence	Small in the leaf axil, solitary, sessile.
Flower	Are yellow, calyx a tube surrounding the inferior ovary, forming at the top 4 lanceolate, acuminate sepals, 2 to 4 mm long, pubescent; petals 4 elliptic a little larger than sepals, stamina 8.
Fruit	Capsule, cylindrical, 4-celled, up to 3 cm long, l to 0.2 mm wide, pubescent, subsessile, somewhat enlarged at top.
Seed	Seed are enclosed in an endocarp.
Biology	Reproduction by seeds.
Ecology	In ever wet regions and in those with a pronounced dry season; in shallow freshwater ditches and pools, edges of water courses, excavated drains, mud, moist garden soils, on inundated soils (where they form pseudo-aerophores). In Java up to 1000 m alt. Lowland-irrigated, rainfed and rice fields.
Origin	The place of origin of this pantropical weed is uncertain.
World Distribution	It is relatively **local in Africa**, Asia and Pacific.
Global Weediness	Is a serious of rice in India, Malaysia, and Sri Lanka and principal weed of rice in Indonesia and Trinidad. It is a **common weed of lowland rice and flood plains of West Africa** and in irrigation lowland rice of East

	Africa.
Local weediness	**Benin**: Frequent but not abundant. Burkina Faso: Frequent but not abundant. Chad: Frequent but not abundant. **Cote d'Ivoire**: Frequent but not abundant. Ghana: Frequent and usually abundant. Mali: Frequent but not abundant. Nigeria: Frequent but not abundant. Senegal: Frequent and usually abundant. Uganda: Rare but abundant when present
Global control	Cultural: hand weeding and tillage are common means of controlling this weed in rice. Chemical control: MCPA and 2,4-D as postemergence treatments and also quinclorac + bensulfuron or molinate + 2,4-D.



Ludwigia hyssopifolia

Source:http://www.afroweeds.org/network/pg/file/read/general-guidelines-for-weed-management-in-lowland-rice

Scientific Publications

Touré, A., Rodenburg, J., Marnotte, P., Dieng, I., and Huat, J. (2014). Identifying problem weeds of rice-based systems along the inland-valley catena in the southern Guinea Savanna. Accepted by *Weed Biology and Management*.

Koné, B., Traoré, K., and **Touré, A.** (2014). Basal Fertilizer Effects on Weed Occurrence and Rice Yield in acid upland soil of West Africa at Bénin. *Journal of Plant Sciences* **2**, 14–22.

Touré, A., Sogbedji, J., and Gumedzoé, D. (2013). The critical period of weed interference in upland rice in northern Guinea savanna: Field measurement and model prediction. *African Journal of Agricultural Research* **8**, 1748–1759.

Koné, B., Amadji, G.L.,**Touré, A.**,Togola, A., Mariko, M., and Huat, J. (2013). A Case of *Cyperus* spp. and *Imperata cylindrica* occurrences on Acrisol of the Dahomey Gap in South Benin as affected by soil characteristics: A strategy for soil and weed management. *Applied and Environmental Soil Science*. doi:org/10.1155/2013/ 601058.

Koné, B., **Touré, A.**, Amadji, G.L., Yao-Kouamé, A., Angui, T. P., and Huat, J. (2012). Soil characteristics and *Cyperus* spp occurrence along a toposequence. *African Journal of Ecology* **51**, 402–408.

Assigbé, P., Koné, B., Bognonkpe, J.P., **Touré, A.**, Huat, J., and Yao-Kouamé, A. (2012). Bush fallow and cowpea crop use as precedent and organic sources of nutrients for rice cultivation on acidic Plinthosol of Central Benin in West Africa. *International Journal of Agriculture Sciences* **4**, 320–324.

Oikeh, S.O., Niang, A., Abaidoo, R., Houngnandan, P., Futakuchi, K., Koné, B., and **Touré, A.** (2012). Enhancing rice productivity and soil nitrogen using dual-purpose cowpea-NERICA® rice sequence in degraded savanna. *Journal of Life Sciences* **6**, 1237–1250.

Touré, A., Rodenburg, J., Saito, K., Oikeh, S., Futakuchi, K., Gumedzoé, D., and Huat, J. (2011). Cultivar and weeding effects on weeds and rice yields in a degraded upland environment of the coastal savanna. *Weed Technology* **25**, 322–329.

Rodenburg, J., Zossou-Kouderin, N., Gbèhounou, G., Ahanchede, A., **Touré, A.**, Kyalo, G., and Kiepe, P. (2011). Rhamphicarpa fistulosa, a parasitic weed threatening rain-fed lowland rice production in sub-Saharan Africa - A case study from Benin. *Crop Protection* **30**, 1306-1314.

Touré, A., Becker, M., Johnson, D.E., Koné, B., Kossou, D.K., and Kiepe, P. (2009). Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Cote d'Ivoire. *Field Crops Research* **114**, 304–310.

Rodenburg, J., Saito, K., Glele, R., **Touré, A.**, Mariko, M., and Kiepe, P. (2009).Weed competitiveness of the lowland rice varieties of NERICA in the southern Guinea Savanna. *Field Crops Research* **114**, 411–418.

Oikeh, S. O., **Touré, A.**, Sidibé, B., Niang, A., Semon, M., Sokei, Y., and Mariko, M. (2009). Responses of upland NERICA rice varieties to nitrogen and plant density. *Archives of Agronomy and Soil Sciences* **55**, 301–314.

Oikeh, S. O., Nwilene, F., Diatta, S., Osiname, O., **Touré, A.,** and Okeleye, K. A. (2008). Responses of upland NERICA rice to nitrogen and phosphorus in forest agroecosystems. *Agronomy Journal* **100**, 735–741.

Nwilene, F.E., Oikeh, S.O., Agunbide, T.A., Oladimeji, O., Ajayi, O., Sié, M., Gregorio, G.B., Togola, A., and **Touré, A.** (2008). Growing lowland rice: a production handbook. AfricaRice, Cotonou, Benin. 33p.

Oikeh, S., Somado, E. A., Sahrawat, K. L., **Touré, A.,** and Diatta, S. (2008). Rice yields enhanced through integrated management of cover crops and phosphate rock in phosphorus-deficient Ultisols in West Africa. *Communications in Soil Sciences and Plant Analysis* **39**, 2894–2919.

Oikeh, S.O., Houngnandan, P., Abaidoo, R.C., Rahimou, I., **Touré, A.**, Niang, A., and Akintayo, I. (2010). Integrated soil fertility management involving promiscuous dual-purpose soybean and upland NERICA enhanced rice productivity in the savannas. *Nutrient Cycling in Agroecosystems* **88**, 29–38.

Touré, A., Mahamane, C. M., Becker, M., and Johnson, D.E. (2005). Approche diagnostique des interventions culturales dans les bas-fonds rizicoles de la Cote d'Ivoire. *Agronomie Africaine* **17**, 219–225.

Akanvou, R., Becker, M., Chano, M., Johnson, D.E., Gbaka-Tchéché, H., and **Touré, A.** (2000). Fallow residue management effects on upland rice in three agroecological zones of West Africa. *Biology and Fertility of Soils* **31**, 501–507.

Ouattara, Z., **Touré, A.,** and Johnson, D.E. (1996). Mise au point d'une technique de culture attelée pour préparation des sols de bas-fond en riziculture: test de labour à la charrue monosoc montée sur bâtis arara. *Agronomie Africaine* **12**, 23–30.

Ouattara, Z., Remington, T., and **Touré, A.** (1994). Test de quelques équipements de préparation des sols hydromorphes de bas-fond en riziculture irriguée ou inondée après une longue jachère. *Agronomie Africaine* **8**, 48-59.

Lao, B., Kanaga, Y., and **Touré, A.** (1990). Etude morpho-pédologigue de la région de Bouaké au 1/100.000ème. Abidjan, BNETD, 48 p. + cartes + annexes.

Posters presentations

Touré, A., Becker, M., Johnson, D.E., Koné, B., Kossou, D.K., and Kiepe, P. (2009). Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Cote d'Ivoire. Poster accepted and presented at the 2nd AfricaRice Congress held at Bamako, Mali (22-24 March 2010).

Touré, A., Marnotte, P., and Huat, J. (2012). Gestion agroécologique des mauvaises herbes dans les bas-fonds rizicoles du Mono et Couffo au sud-Bénin. First price in posters competition organized by France Embassy in Benin.

Touré, A., Marnotte, P., Huat, J., Mariko, M., and Kossou, D. (2013). Identifying problem weeds of rice based systems along the inland valley catena in the southern Guinea Savannah. Poster accepted and presented at the 3rd AfricaRice Congress held at Yaoundé, Cameroon (21-24 October 2013).

Touré, A., Huat, J., and Marnotte, P. (2013). La gestion des mauvaises herbes auxiliaires dans les systèmes de production de riz de bas-fond. Poster accepted and presented at the 22th Columa Conference held at Dijon, France (10-12 December 2013).

.

References

Achigan-Dako, E. G., N'danikou, S., Assogba-Komlan, F., Ambrose-Oji, B., Ahanchede, A., and Pasquini, M. W. (2011). Diversity, geographical, and consumption patterns of traditional vegetables in sociolinguistic communities in Benin: Implications for domestication and utilization. *Economic Botany* **10**, 1–17.

Adesina, A. A., Johnson, D. E., and Heinrichs, E. A. (1994). Rice pests in the Cote d'Ivoire, West Africa-farmers perceptions and management strategies. *International Journal for Pest Management* **40**, 293–299.

AfricaRice (2011). "Boosting Africa's Rice sector: A research for development strategy 2011-2020." Africa Rice Center, Cotonou, Benin.

Ahanchede, A., and Gasquez, J. (1997). Weeds of Rainfed Crop Fields in Northeastern Benin. *In* "Agriculture et Développement", pp. 17–23. Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Montpellier, France.

Akanvou, R., Becker, M., Chano, M., Johnson, D. E., Gbaka-Tcheche, H., and Touré, A. (2000). Fallow residue management effects on upland rice in three agroecological zones of West Africa. *Biology and Fertility of Soils* **31**, 501–507.

Akintoye, H. A., Adebayo, A. G., and Aina, O. O. (2011). Growth and yield response of okra intercropped with live mulch. *Asian Journal ofAgricultural Research* **5**, 146 – 153.

Akobundu, I. O. (1980). Weed science research at the International Institute of Tropical Agriculture and research needs in Africa. *Weed Science* **28**, 439–445.

Akobundu, I. O. (1987). "Weed science in the tropics. Principles and practices.," John Wiley & Sons.

Akobundu, I. O., and Agyakwa, C. W. (1987). "A handbook of West African Weeds," International Institute of Tropical agriculture, Ibadan, Nigeria.

Akobundu, I. O., and Ahissou, A. (1985). Effect of interrow spacing and weeding frequency on the performance of selected rice cultivars on hydromorphic soils of West Africa *Crop Protection* **4**, 71–76.

Akobundu, I. O., Ekeleme, F., and Chikoye, D. (1999). Influence of fallow management systems and frequency of cropping on weed growth and crop yield. *Weed Research* **39**, 241–256.

Altieri, M. A., Funes-Monzote, F. R., and Petersen, P. (2012). Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. *Agronomy for Sustainable Development* **32**, 1–13.

Ampong-Nyarko, K., and De Datta, S. K. (1989). Ecophysiological studies in relation to weed management strategies in rice. *In* "12th Asian-Pacific Weed Science Society Conference", pp. 31–46, Seoul, Korea.

Andersen, E., Elbersen, B., Godeschalk, F., and Verhoog, D. (2007). Farm management indicators and farm typologies as a basis for assessments in a changing policy environment. *Journal of environmental management* **82**, 353–362.

Andriesse, W., and Fresco, L. O. (1991). A characterization of rice-growing environments. *Agriculture, Ecosystems and Environment* **33**, 377–395.

Andriesse, W., Fresco, L. O., Duivenbooden, N., and Windmeijer, P. N. (1994). Multi-scale characterization of inland valley agro-ecosystems in West Africa. *Netherlands Journal of Agricultural Science* **42**, 159–179.

Ashraf, M., Palada, M. C., Masajo, T. M., and Wakatsuki, T. (1988). Rice-based cropping systems for inland valleys and their improvement possibilities in Nigeria. *In* "Improved agricultural technologies for small-scale Nigerian farmers" (O. G. I. Abalu and B. A. Kalu, eds.), pp. 149–171. Nigeria Farming Systems Research Network, Los , Nigeria.

Assogba, T., Huat, J., and Assogba-Komlan, F. (2011). "Caractérisation et analyse du fonctionnement des systèmes de culture dans les zones de bas-fonds : cas des communes de Dogbo et de Houéyogbé (Département du Mono – Couffo, Bénin)." INRAB & AfricaRice, Cotonou, Benin.

Asubonteng, K. O., Kubota, D., Hayashi, K., Masunaga, T., Otoo, E., and Wakatsuki, T. (2001). Effect of a sawah-based farming system on rice cultivation in the inland valley bottom of the Ashanti region of Ghana. *Tropics* **10**, 555–564.

Aubry, C., and Michel-Dounias, I. (2006). Systèmes de culture et décisions techniques dans l’exploitation agricole. *In* "L’agronomie aujourd’hui" (T. Doré, M. Le Bail, P. Martin, B. Ney and J. Roger-Estrade, eds.), pp. 57–75. Quae, collection Synthèses, Paris, France.

Aulakh, M. S., and Grant, C. A. (2008). "Integrated nutrient management for sustainable crop production," The Haworth Press, New York, USA.

Balasubramanian, V., Sié, M., Hijmans, R. J., and Otsuka, K. (2007). Increasing rice production in Sub-Saharan Africa: challenges and opportunities. *Advances in Agronomy* **94**, 55–133.

Barralis, G., and Chadœuf, R. (1980). Etude de la dynamique d'une communauté adventice.I. Evolution de la flore adventice au cours du cycle végétatif d'une culture. *Weed Research* **20**, 231–237.

Beaudou, A. G., and Sayol, R. (1980). "Etude pédologique de la région de Boundiali-Korhogo (Cote d’Ivoire)," Rep. No. 84, Paris, France.

Becker, L., and Diallo, R. (1992). Characterization and classification of rice agro-ecosystems in Cote d'Ivoire. pp. 135 West Africa Rice Development Association (WARDA), Bouaké, Cote d'Ivoire.

Becker, M. (2008). Potential of organic substrates in lowland rice-based systems of Asia. *In* "Organic agriculture in the tropics and subtropics" (U. Köpke, ed.), pp. 17–28, Verlag Dr. Köster, Berlin, Germany.

Becker, M., Dalton, T. J., and Johnson, D. E. (1997). The role of legumes in lowland rice-based systems of Cote d'Ivoire. *Inland Valley Newsletter* **3**, 15–17.

Becker, M., and Johnson, D. E. (1999a). Rice yield and productivity gaps in irrigated systems of the forest zone of Cote d'Ivoire. *Field Crops Research* **60**, 201–208.

Becker, M., and Johnson, D. E. (1999b). The role of legume fallows in intensified upland rice-based systems of West Africa. *Nutrient Cycling in Agroecosystems* **53**, 71 – 81.

Becker, M., and Johnson, D. E. (2001). Improved water control and crop management effects on lowland rice productivity in West Africa. *Nutrient Cycling in Agroecosystems* **59**, 119–127.

Becker, M., Johnson, D. E., Wopereis, M. C. S., and Sow, A. (2003). Rice yield gaps in irrigated systems along an agro-ecological gradient in West Africa. *Journal of Plant Nutrition and Soil Science* **166**, 61–67.

Becker, M., Maskey, S. L., Pande, K. R., Shah, S. C., and Shrestha, S. C. (2007). Effects of transition season management on soil N dynamics and system N balances in rice-wheat rotations of Nepal. *Field Crops Research* **103**, 98–108.

Beets, W. C. (1990). "Raising and sustaining productivity of smallholder farming systems in the tropics," AgBé P.O. Box 9125 1800 GC, Alkmaar, Holland.

Berry, S. S. (1993). "No Condition Is Permanent: The Social Dynamics of Agrarian Change in Sub-Saharan Africa," University of Wisconsin Press, Madison, WI.

Bida, G., and Pluvinage, J. (2006). La pluriactivité dans l’exploitation agricole, transition ou composante durable de l’organisation de la production en Albanie. *Cahiers Agricultures* **15**, 535–541.

Bidogeza, J. C., Berentsen, P. B. M., De Graaff, J., and Oude Lansink, A. G. J. M. (2009). A typology of farm households for the Umutara Province in Rwanda. *Food Security* **1**, 321–335.

Blandin, P. (1992). De l’écosystème à l’écocomplexe. *In* "Sciences de la Nature, Sciences de la Société / Les passeurs de frontières" (M. Jollivet, ed.), pp. 267 – 279. CNRS, Paris, France.

Blazy, J. M., Ozier-Lafontaine, H., Doré, T., Thomas, A., and Wery, J. (2009). A methodological framework that accounts for farm diversity in the prototyping of crop management systems. Application to banana-based systems in Guadeloupe. *Agricultural systems* **101**, 30–41.

Bognonkpe, J. P. I. (2004). Effect of land use on soil N dynamics at watershed scale in Africa, Bonn, Bonn, Germany.

Bognonkpe, J. P. I., and Becker, M. (2000). Native soil N dynamics and use efficiency by lowland rice as a function of slope management. *In* "International Agricultural Research: A contribution to crisis prevention" (T.-U. o. Hohenheim, ed.), pp. 197–199.

Boiffin, J., Malézieux, E., and Picard, D. (2001). Cropping systems for the future. *In* "Crop science; progress and prospect" (J. Nösberger, H. H. Geiger and P. C. Struik, eds.), pp. 261-279. CAB International, Oxon, U.K.

Boling, A. A., Tuong, T. P., Suganda, H., Konboon, Y., Harnpichitvitaya, D., Bouman, B. A. M., and Franco, D. T. (2008). The effect of toposequence position on soil properties, hydrology, and yield of rainfed lowland rice in Southeast Asia. *Field Crops Research* **106**, 22–33.

Bray, F. (1986). "The rice economies," Blackwell, Oxford, U. K.

Brossier, J. (1987). Système et système de production ; Note sur ces concepts. *Cahiers des Sciences Humaines* **23**, 377–390.

Burkill, H. M. (2004). "The Useful Plants of West Tropical Africa." Kew, England, Royal Botanic Gardens.

Carsky, R. J., and Masajo, T. M. (1992). Effect of toposequence position on performance of rice varieties in inland valleys of West Africa. *In* "Resource and Crop Management Research Monograph ", International Institute of Tropical Agriculture, Ibadan.

Cassman, K. G., Gines, G. C., Dizon, M. A., Samson, M. L., and Alcantara, J. M. (1996). Nitrogen use efficiency in tropical lowland rice systems: Contributions from indigenous soil resources and applied nitrogen inputs. *Field Crops Research* **47**, 1-12.

Castillo, E. G., Buresh, R. J., and Ingram, K. T. (1992). Lowland rice yield as affected by timing of water deficit and nitrogen fertilization. *Agronomy Journal* **84**, 152–159.

Chayanov, A. (1990). "L’organisation de l’économie paysanne," Librairie du regard, Alençon, France.

Chia, E., Dugué, P., and Sakho-Jimbira, S. (2006). Les exploitations agricoles familiales sont-elles des institutions ? *Cahiers Agricultures* **15**, 498–505.

Chikoye, D., and Ekeleme, F. (2001). Weed flora and soil seedbanks in fields dominated by *Imperata cylindrica* in the moist savannah of West Africa. *Weed Research* **41**, 475–490.

Crowley, E. L., and Carter, S. E. (2000). Agrarian change and the changing relationships between toil and soil in Maragoli, Western Kenya (1900–1994). *Human Ecology Review* **28**, 383–414.

Dalgaard, R., Halberg, N., Kristensen, I. S., and Larsen, I. (2006). Modelling representative and coherent Danish farm types based on farm accountancy data for use in environmental assessments. *Agriculture, Ecosystems & Environment* **117**, 223–237.

Daskalopoulou, I., and Petrou, A. (2002). Utilising a farm typology to identify potential adopters of alternative farming activities in Greek agriculture. *Journal of Rural Studies* **18**, 95–103.

De Datta, S. K. (1981). "Principles and practices of rice production," John Wiley, New York.

De Datta, S. K., and Baltazar, A. M. (1996). Weed control technology as a component of rice production systems. *In* "Weed management in rice" (B. A. Auld and K.-U. Kim, eds.), Vol. 139, pp. 27–52. FAO Plant Production and Protection Rome, Italy.

De Rouw, A. (1991). Rice, weeds and shifting cultivation in a tropical rain forest. A study of vegetation dynamics, Wageningen Agricultural University, Wageningen, the Netherlands.

De Rouw, A. (1995). The fallow period as a weed-break in shifting cultivation (tropical wet forests). *Agriculture Ecosystems & Environment* **54**, 31–43.

De Vida, F. B. P., Laca, E. A., Mackill, D. J., Grisel, M., and Fischer, A. J. (2006). Relating rice traits to weed competitiveness and yield; a path analysis. *Weed Science* **54**, 1122–1131.

Deléage, J.-P. (1991). "Une histoire de l'écologie," Paris, Points-Seuil.

Dingkuhn, M., Johnson, D. E., Sow, A., and Audebert, A. Y. (1999). Relationships between upland rice canopy characteristics and weed competitiveness. *Field Crops Research* **61**, 79–95.

Doggett, H. (1984). Striga-advances in control. *In* "Advancing Agricultural Production in Africa" (D. L. Hawsworth, ed.), pp. 81–85. Commonwealth Agricultural Bureaux, Slough, UK.

Dogliotti, S., van Ittersum, M. K., and Rossing, W. A. H. (2006). Influence of farm resource endowment on possibilities for sustainable development: a case study for vegetable farms in South Uruguay. *Journal of Environmental Management* **78**, 305–315.

Doré, T., Clermont-Dauphin, C., Crozat, Y., David, C., Jeuffroy, M. H., Loyce, C., Makowski, D., Malézieux, E., Meynard, J. M., and Valantin-Morison, M. (2008). Methodological progress in on-farm regional agronomic diagnosis A review. *Agronomy for Sustainaible Development* **28**, 151–161.

Doré, T., Sebillotte, M., and Meynard, J. M. (1997). A diagnostic method for assessing regional variations in crop yield. *Agricultural Systems* **54**, 169–188.

Dounias, I., Aubry, C., and Capillon, A. (2002). Decision-making processes for crop management on African farms Modelling from a case study of cotton in northern Cameroon. *Agricultural Systems* **73**, 233– 260.

Dufumier, M. (2006). Diversité des exploitations agricoles et pluriactivité des agriculteurs dans le Tiers Monde. *Cahiers Agricultures* **15**, 584–588.

Dvorsky, M., Dolezal, J., De Bello, F., Klimesova, J., and Klimes, L. (2011). Vegetation types of East Ladakh: species and growth form composition along main environmental gradients. *Applied Vegetation Science* **14**, 132–147.

Edwards, E. J., and Smith, S. A. (2010). Phylogenetic analyses reveal the shady history of C_4 grasses. *Proceedings of the National Academy of Sciences* **107**, 2532–2537.

Ehleringer, J., Cerling, T., and Helliker, B. (1997). C_4 photosynthesis, atmospheric CO2 and Climate. *Oecologia* **112**, 285–299.

Elmore, C. D., and Paul, R. N. (1983). Composite list of C_4 weeds. *Weed Science* **31**, 686–692.

Elmquist, T., Folke, C., Nystrom, M., Peterson, G., Bengtsson, J., Walker, B., and Norberg, J. (2003). Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment* **1**, 488–494.

Erenstein, O. (2006a). Intensification or extensification ? Factors affecting technology use in peri-urban lowlands along an agro-ecological gradient in West Africa. *Agricultural Systems* **90**, 132–158.

Erenstein, O., Sumberg, J., Oswald, A., Levasseur, V., and Koré, H. (2006b). What future for integrated rice-vegetable production systems in West African lowlands? . *Agricultural Systems* **88**, 376–394.

Escalada, M. M., and Heong, K. L. (2004). A participatory exercise for modifying rice farmers' beliefs and practices in stem borer loss assessment. *Crop Protection* **23**, 11–17.

FAO (1998). World reference base for soil resources. World Soil Resources Report 84, Food and Agriculture Organization of the United Nations, Rome.

FAO (2010). Rice and us. http://www.fao.org/rice2010/en/aboutrice.htm.

Feder, G., and Noronha, R. (1987). Land rights systems and agricultural development in Sub-Saharan Africa. *World Bank Research Observer* **2**, 143–169.

Fehlberg, H. G. (1989). Shifting cultivation – some management aspects for its improvement. *In* "Nutrient management for food crop production in tropical farming systems" (J. v. d. Heide, ed.), pp. 381–394. Institute for Soil Fertility, Haren, the Netherlands/Universitas Brawijaya, Malang, Indonesia.

Feuillette, B., Marnotte, P., and Le Bourgeois, T. (1997). *Imperata cylindrica*. *In* "Agriculture et Développement", pp. 66–67. Centre de Cooperation Internationale en Recherche Agronomique, Montpellier, France.

Fleischer, G., Andoli., V., Coulibaly, M., and Randolph, T. (1998). Analyse socio-économique de la filière des pesticides en Côte d' Ivoire. (I. d. S. Economiques, ed.), pp. 86. University of Hanover, Hanoverr, Germany.

Fofana, B., and Rauber, R. (2000). Weed suppression ability of upland rice under low-input conditions in West Africa. *Weed Research* **40**, 271–280.

Fresco, L.O., and Kroonenberg, S.B. (1992). Time and spatial scales in ecological sustainability. *Land Use Policy* 9, 155–168.

Fuhrer, J. (2003). Agroecosystem responses to combinations of elevated CO2, ozone, and global climate change. *Agriculture, Ecosystems and Environment* **97**, 1–20.

Galán, M., Hagen, M. A., and Vicente Orellana, J. A. (1999). Aerophyte, a new life form in Raunkiær's classification? *Journal of Vegetation Science* **10**, 65–68.

Gastellu, J. M. (1980). Mais où sont donc ces unités économiques que nos amis cherchent tant en Afrique ? . *Cahiers Orstom Série Sciences Humaines* **17**, 157–161.

George, T., Ladha, J. K., Buresh, R. J., and Garrity, D. P. (1993). Nitrate dynamics during the aerobic soil phase in lowland rice-based cropping systems. *Soil Science Society of America Journal* **57**, 1526–1532.

George, T., Magbanua, R., Garrity, D. P., Tubana, B. S., and Quiton, J. (2002). Rapid yield loss of rice cropped successively in aerobic soil. *Agronomy Journal* **94**, 981–989.

Gibson, K. D., Fischer, A. J., Foin, T. C., and Hill, J. E. (2003). Crop traits related to weed suppression in water-seeded rice (Oryza sativa L.). *Weed Science* **51**, 87–93.

Giertz, S., Steup, G., and Schönbrodt, S. (2012). Use and constraints on the use of inland valley ecosystems in central Benin: results from an inland valley survey. *Erkunde* **66**, 239–253.

Giller, P. S., Hillebrand, H., Berninger, U. G., Gessner, M. O., Hawkins, S., Inchausti, P., Inglis, C., Leslie, H., Malmqvist, B., Monaghan, M. T., Morin, P. J., and O'Mullan, G. (2004). Biodiversity effects on ecosystem functioning: emerging issues and their experimental test in aquatic environments. *Oikos* **104**, 423–436.

Gliessman, S. R. (1997). "Agroecology: Ecological Processes in Sustainable Agriculture," CRC Press.

Grard, P., Le Bourgeois, T., Rodenburg, J., Marnotte, P., Irakiza, R., Makokha, D..*et al.* (2013. AFROweeds V. 1.0: African Weeds of Rice. CIRAD-AfricaRice, Montpellier, France and Cotonou, Benin.

Greenland, D. J. (1975). Bringing the green revolution to the shifting cultivator. *Science* **190**, 841–844.

Haefele, S. M., Jabbar, S. M. A., Siopongco, J. D. L. C., Tirol-Padre, A., Amarante, S. T., Sta Cruz, P. C., and Cosico, W. C. (2008). Nitrogen use efficiency in selected rice (*Oryza sativa* L.) genotypes under different water regimes and nitrogen levels. *Field Crops Research*, 137–146.

Haefele, S. M., Johnson, D. E., Bodj, D. M., Wopereis, M. C. S., and Miezan, K. M. (2004). Field screening of diverse rice genotypes for weed competitiveness in irrigated lowland ecosystems. *Field Crops Research* **88**, 39–56.

Haefele, S. M., Wopereis, M. C. S., and Donovan, C. (2002). Farmers' perceptions, practices and performance in a Sahelian irrigated rice scheme. *Experimental Agriculture* **38**, 197–210.

Hamma, I. L., Ibrahim, U., and Yusuf, S. M. (2012). Growth and yield of okra as influenced by live mulch in Samaru, Zaria. *European Journal of Sustainable Development* **1**, 229–234.

Hanzlik, K., and Gerowitt, B. (2011). The importance of climate, site and management on weed vegetation in oilseed rape in Germany. *Agriculture Ecosystems and Environment* **141**, 323–331.

Hawes, C., Squire, G. R., Hallett, P. D., Watson, C. A., and Young, M. (2010). Arable plant communities as indicators of farming practice. *Agriculture Ecosystems and Environment* **138**, 17–26.

Heong, K. L., Escalada, M. M., Huan, N. H., and Mai, V. (1998). Use of communication media in changing rice farmers' pest management in the Mekong Delta, Vietnam. *Crop Protection* **17**, 413-425.

Heong, K. L., Escalada, M. M., Sengsoulivong, V., and Schiller, J. (2002). Insect management beliefs and practices of rice farmers in Laos. *Agriculture Ecosystems & Environment* **92**, 137–145.

Hirose, S. (2002). Agronomic evaluation on the preliminary trials on Sawah farming in Gadza during 1992-1995. *In* "Restoration of inland valley ecosystems in West Africa" (S. Hirose and T. Wakatsuki, eds.), pp. 572. Association of agriculture and Forestry Statistics, Megro-ku, Tokyo 153-0064, Japan.

Hossain, M., and Fischer, K. S. (1995). Rice research for food security and sustainable GeoJournalagricultural development in Asia: Achievements and future challenges. *GeoJournal* **35**, 286–298.

Huat, J., Doré, T., and Aubry, C. (2013). Limiting factors for yields of field tomatoes grown by smallholders in tropical regions. *Crop Protection* **44**, 120–127.

Huffman, L. F. (1987). "Women's activities and impact on child nutrition," London, UK.

[IITA] International Institute of Tropical Agriculture (1989). Automated and semi-automated methods for soil and plant analysis. Manual series No. 7. IITA, Ibadan, Nigeria, p. 33.

Iiyama, M., Kariuki, P., Kristjanson, P., Kaitibie, S., and Maitima, J. (2008). Livelihood diversification strategies, incomes and soil management strategies: a case study from Kerio valley, Kenya. *Journal of International Development* **20**, 380–397.

Iraizoz, B., Gorton, M., and Davidova, S. (2007). Segmenting farms for analysing agricultural trajectories: A case study of the Navarra region in Spain. *Agricultural systems* **93**, 143–169.

IRRI (2002). "Rice Almanac," Los Banõs, Philippines.

Issaka, R. N., Buri, M. M., and Wakatsuki, T. (2009). Effect of soil and water management practices on the growth and yield of rice in the forest agro-ecology of Ghana. *Journal of Food Agriculture and Environment* **7**, 214–218.

Izac, A. M., and Tucker, E. (1991). Analyse systématique des agrosystèmes de bas-fond en Afrique occidentale. *In* "Bas-fonds et riziculture" (M. Raunet, ed.), pp. 203–211. CIRAD, Montpellier, France, Antananarivo, Madagascar.

Jansen, H. G. P., Rodriguez, A., Damon, A., Pender, J., Chenier, J., and Schipper, R. (2006). Determinants of income-earning strategies and adoption of conservation practices in hillside communities in rural Honduras. *Agricultural Systems* **88**, 92–110.

Jennings, P. R., and Aquino, R. C. (1968). Studies on competition in rice. III. The mechanism of competition among phenotypes. *Evolution* **22**, 529–542.

Jennings, P. R., and Herrera, R. M. (1968). Studies on competition in rice. II. Competition in segregating populations. *Evolution* **22**, 332–336.

Jennings, P. R., and Jesus Jr, J. D. (1968). Studies on competition in rice. I. Competition in mixtures of varieties. *Evolution* **22**, 119–124.

Joffre, O. M., and Bosma, R. H. (2009). Typology of shrimp farming in Bac Lieu Province, Mekong Delta, using multivariate statistics. *Agriculture, Ecosystems and Environment* **132**, 153–159.

Johnson, D. E. (1996). Weed management in small holder rice production in the tropics. IPM Word Textbook, University of Minnesota, St. Paul, MN.

Johnson, D. E. (1997). "Weeds of rice in West Africa," WARDA, Bouaké, Cote d'Ivoire.

Johnson, D. E., and Adesina, A. A. (1993). Farmers perceptions of riceweeds and control measures in Cote d'Ivoire, West africa. *In* "Brighton Crop Protection Conference – Weeds", pp. 1143–1147, London, UK.

Johnson, D. E., Dingkuhn, M., Jones, M. P., and Mahamane, M. C. (1998). The influence of rice plant type on the effect of weed competition on O.glaberrima and O. sativa. *Weed Research* **38**, 207–216.

Johnson, D. E., and Kent, R. J. (2002). The impact of cropping on weed species composition in rice after fallow across a hydrological gradient in west Africa. *Weed Research* **42**, 89–99.

Johnson, D. E., Wopereis, M. C. S., Mbodj, D., Diallo, S., Powers, S., and Haefele, S. M. (2004). Timing of weed management and yield losses due to weeds in irrigated rice in the Sahel. *Field Crops Research* **85**, 31–42.

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J., and Ritchie, J. T. (2003). The DSSAT cropping system model. *European Journal of Agronomy* **18**, 235–265.

Jones, M. P., Johnson, D. E., and Kouper, T. (1996). Selection for weed competitiveness in upland rice. *International Rice Research Notes* **21**, 32–33.

Jones, M. P., Mande, S., and Alluko, K. (1997). Diversity and potential of O. glaberrima Steud. Progenies in upland rice improvement. *Euphytica* **92**, 237–246.

Jouve, P. (1990). L'analyse agronomique de situations culturales. *In* "Agronomie et ressources naturelles en régions tropicales" (R. Bertrand and H. Saint Macary, eds.), pp. 127–135. CIRAD-IRAT, Montpellier, France.

Jouve, P. (1992). Le diagnostic du milieu rural: de la région à la parcelle. Approche systémique des modes d'exploitation agricole du milieu. *In* "L'appui aux producteurs" (M. d. l. C. e. d. Développement, ed.), pp. 65–98, Paris, France.

Jouve, P. (1997). Des techniques aux pratiques. Conséquences méthodologiques pour l'étude des systèmes de production agricole et le développement rural. *In* "Acte du colloque Méthodes pour comprendre et mesurer les pratiques agraires en milieu tropical et leurs transformations", pp. 101-114. IGUL/Université A. Moumouni, Niamey, Niger.

Kawano, K., Gonzalez, H., and Lucena, M. (1974). Intraspecific competition, competition with weeds, and spacing response in rice. *Crop Science* **14**, 841–845.

Kent, R. J., and Johnson, D. E. (2001). Influence of flood depth and duration on growth of lowland rice weeds, Cote d'Ivoire. *Crop Protection* **20**, 691–694.

Kent, R. J., Johnson, D. E., and Becker, M. (2001). The influences of cropping system on weed communities of rice in Cote d'Ivoire, West Africa. *Agriculture, Ecosystems and Environment* **87**, 299–307.

Koarai, A., and Morita, H. (2003). Evaluation of the suppression ability of rice (Oryza sativa) on Monochoria vaginalis by measuring photosynthetic photon flux density below rice canopy. *Weed Biology and Management* **3**, 172–178.

Köbrich, C., Rehman, T., and Khan, M. (2003b). Typification of farming systems for constructing representative farm models: two illustrations of the application of multivariate analyses in Chile and Pakistan. *Agricultural Systems* **76**, 141–157.

Kossou, D. K., Gbèhounou, G., Ahanchédé, A., Ahohouendo, B., Bouraïma, Y., and van Huis, A. (2001). Indigenous cowpea production and protection. *Insect Science Application* **21**, 123–132.

Kranjac-Berisavljevic, G., Laryea, K. B., Abenney-Mickson, S., Mahama, S., and Alhassan, R. (2002). "A study of appropriate bunding methods for rainfed rice in Northern Ghana.," Tamale, Ghana.

Kropff, M., Bouma, J., and Jones, J. W. (2001). Systems approaches for the design of sustainable agro-ecosystems. *Agricultural Systems* **70**, 369–393.

Ladha, J. K., Kirk, G. J. D., Bennet, J., Peng, S., Reddy, C. K., Reddy, P. M., and Singh, U. (1998). Opportunities for increased nitrogen-use efficiency from improved lowland rice germplasm. *Field Crops Research* **56**, 41–71.

Landais, E. (1998). Modelling farm diversity new approaches to typology building in France. *Agricultural Systems* **58**, 505–527.

Le Bourgeois, T., and Marnotte, P. (2002). La lutte contre les mauvaises herbes. *In* "Mémento de l'Agronome" (M. d. A. E. CIRAD-GRET, ed.), pp. 663–684, Paris.

Le Bourgeois, T., and Merlier, H. (1995). "Adventrop. Les mauvaises herbes d'Afrique soudano-sahélienne," Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Montpellier, France.

Le Meur, P. Y. (2002). Trajectories of the politicisation of land issues: case studies from Benin. *In* "Negotiating property in Africa" (K. Juul and C. Lund, eds.), pp. 135–155. Heinemann, Portsmouth, U.K.

Lemerle, D., Gill, G. S., Murphy, C. E., Walker, S. R., Cousens, R. D., Mokhtari, S., Peltzer, S. J., Coleman, R., and Luchett, D. J. (2001). Genetic improvement and agronomy for enhanced wheat competitiveness with weeds. *Australian Journal of Agricultural Research* **52**, 527–548.

Loomis, R. S., and Connor, D. J. (1992). "Crop ecology-productivity and management in agricultural systems," Cambridge University Press, Cambridge, UK.

Loreau, M., Naeem, S., and Inchausti, P. (2002). "Biodiversity and Ecosystem Functioning: Synthesis and Perspectives," Oxford University Press., Oxford (United Kingdom).

Mahmud, W., Rahman, S. H., and Zohir, S. (1994). "Agricultural growth through crop diversification in Bangladesh." International Food Policy Research Institute, Washington, DC USA.

Marnotte (1997). Herbicide use: constraints and prospects. *Agriculture et Développement* **9**, 2–10.

Marnotte, P., Perret, D., and Carrara, A. (2004). Enquête sur l'enherbement des rizières de Camargue (France). *In* "Douzième Colloque international sur la biologie des mauvaises herbes, AFPP", Dijon, France.

Mathieu, B. (2005). Une démarche agronomique pour accompagner le changement technique. Cas de l'emploi du traitement herbicide dans les systèmes de cutlure à sorgho repiqué au Nord-Cameroun, Thèse doctorat, Institut National Agronomique Paris-Grignon, Paris, France.

Maton, L., Leenhardt, D., Goulard, M., and Bergez, J. E. (2005). Assessing the irrigation strategies over a wide geographical area from structural data about farming systems. *Agricultural systems* **86**, 293–311.

McCloskey, Firbank, L. G., Watkinson, A. R., and Webb, D. J. (1996). The dynamics of experimental arable weed communities under different management practices. *Journal of Vegetation Science* **7**, 799–808.

McCown, R. L. (2002). Changing systems for supporting farmers' decisions: problems, paradigms and prospects. *Agricultural Systems* **74**, 179–220.

McCullagh, P., and Nelder, J. A. (1989). "Generalized Linear Models " Second/Ed. Chapman and Hall, London, United Kingdom.

Meynard, J. M., Doré, T., and Habib, R. (2001). L'évaluation et la conception de systèmes de culture pour une agriculture durable. *Compte rendu Académie Agriculture France* **87**, 223–236.

Michels, T. (2005). Adapter la conduite des plantations d'hévéa à la diversité des exploitations villageoises (étude de cas au Cameroun), Thèse doctorat, Institut National Agronomique Paris- Grignon, Paris, France.

Michels, T., Bissery, C., and Jannoyer, M. (2009). Two scales approach to characterize farmers' practices. *In* "Farming systems design: methodologies for integrated analysis of farm production systems" (J. L. Hatfield, M. Donatelli, P. Carberry, A. Rizzoli and J. Jones, eds.), pp. 141–142, Monterey, CA, USA.

Milleville, P., and Serpantié, G. (1991). Regards sur l'élaboration de la production agricole en agriculture paysanne tropicale: problèmes de méthodes. *In* "Seminfor 5: Cinquième Séminaire Informatique " (ORSTOM, ed.), pp. 107-123, Montpellier, France.

Moody, K. (1996). Weed community dynamics in rice fields. In: Herbicides in Asian rice: Transitions in weed management. (R. Naylor, ed.), pp. 27–35, Institute for International Studies, Stanford University, Palo Alto, USA and International Rice Research Institute, Manila, The Philippines.

Moody, K., and Cordova, V. G. (1985). "Wet-seeded rice." International Rice Research Institute (IRRI), Los Banõs, Philippines.

Moormann, F. R., and Juo, A. S. R. (1986). Present land use and cropping systems in Africa. *In* "The Wetlands and rice in Subsaharan Africa" (A. S. R. Juo and J. A. Lowe, eds.), pp. 318. IITA, Ibadan, Nigeria.

Murdock, J. N., Gido, K. B., Dodds, W. K., Bertrand, K. N., and Whiles, M. R. (2010). Consumer return chronology alters recovery trajectory of stream ecosystem structure and function following drought. *Ecology* **91**, 1048–1062.

Ni, H., Moody, K., Robles, R. P., Paller, E. C., and Lales, J. S. (2000). Oryza sativa plant traits conferring competitive ability against weeds. **48**, 200–204.

Nieto, J. H., Brondo, M. A., and Gonzalez, J. T. (1968). Critical periods of the growth cycle for competition from weeds. *PANS (C)* **14**, 159–168.

Obemines (1989). "Carte géologique du Bénin à 1:200 000," Minstère des Mines et Géologie Cotonou, Bénin.

Oerke, E.-C., and Dehne, H.-W. (2004). Safeguarding production-losses in major crops and the role of crop protection. *Crop Protection* **23**, 275–285.

Ogban, P. I., and Babalola, O. (2009). Characteristics, classification and management of inland valley bottom soil for crop production in sub-humid southwestern Nigeria. *Agro-Science* **8**, 1 – 13.

Oikeh, S. O., Nwilene, F., Diatta, S., Osiname, O., Touré, A., and Okeleye, K. A. (2008). Responses of upland NERICA rice to nitrogen and phosphorus in forest agroecosysytems. *Agronomy Journal* **100**, 735–741.

Oomen, J. M. V., de Wolf, J., and Jobin, W. R. (1990). "Health and irrigatiom: incorporation of disease-control measures in irrigation, a multi faceted task in design, construction, operation.." ILRI, Wageningen, The Netherlands.

Papy, F. (2001). Interdépendance des systèmes de culture dans l'exploitation. *In* "Modélisation des agrosystèmes et aide à la décision" (E. Malézieux, G. Trébuil and M. Jaeger, eds.), pp. 51–74. CIRAD/INRA, Paris.

Papy, F. (2004). Formuler les problèmes de mise en œuvre des techniques, comprendre les pratiques, penser l'innovation. *In* "Agro-tribulations" (C. Blanc-Pamard, ed.), pp. 59–67, Paris L'amitié Pierre-Louis Osty.

Paul, J.-L., Bory, A., Bellande, A., Garganta, E., and Fabri, A. (1994). "Quel système de référence pour la prise en compte de la rationalité de l'agriculteur : du système de production agricole au système d'activité." *Les Cahiers de la Recherche/Développement* **39**, 7–19.

Pithayanukul, P., Laovachirasuwan, S., Bavovada, R., Pakmanee, N., and Suttisri, R. (2004). Anti-venom potential of butanolic extract of *Eclipta prostrata* against Malayanpit viper venom. *Journal of Ethnopharmacology* **90**, 347– 352.

PNE-Benin (2009). "Identification de sites pilotes et d'évaluation des actions de promotion de la gestion intégrée des ressources en eau (GIRE) locale dans les départements du Mono et du Couffo," Porto Novo, Bénin.

Poussin, J. C., Imache, A., Beji, R., Le Grusse, P., and Benmihoub, A. (2008). Exploring regional irrigation water demand using typologies of farms and production units: An example from Tunisia. *Agricultural Water Management* **95**, 973–983.

R Core, T. (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria.

Rao, A. N., Johnson, D. E., Sivaprasad, B., Ladha, J. K., and Mortimer, A. M. (2007). Weed management in direct-seeded rice. *Advances in Agronomy* **93**, 153–255.

Raunet, M. (1985). Bas-fonds et riziculture en Afrique, approche structurale et comparative. *L'Agronomie Tropicale* **40**, 181– 201.

Richards, P. (1986). "Coping with hunger: hazard and experiment in an African rice farming system," Allen and Unwin, London, England.

Rodenburg, J., Both, J., Heitkönig, I. M. A., van Koppen, C. S. A., Sinsin, B., Van Mele, P., and Kiepe, P. (2012). Land-use and biodiversity in unprotected landscapes: The case of non cultivated plant use and management by rural communities in Benin and Togo. *Society and Natural Resources* **25**, 1221–1240.

Rodenburg, J., and Demont, M. (2009). Potential of Herbicide-Resistant Rice Technologies for Sub-Saharan Africa. *AgBioForum* **12**, 313–325.

Rodenburg, J., and Johnson, D. E. (2009). Weed management in rice-based cropping systems in Africa. *Advances in Agronomy* **103**, 149–218.

Rodenburg, J., Meinke, H., and Johnson, D. E. (2011). Challenges for weed management in African rice systems in a changing climate. *The Journal of Agricultural Science* **149**, 427–435.

Rodenburg, J., Saito, K., Glele, R., Touré, A., Mariko, M., and Kiepe, P. (2009). Weed competitiveness of the lowland rice varieties of NERICA in the southern Guinea Savanna. *Field Crops Research* **114**, 411–418.

Rodenburg, J., Zwart, S., Kiepe, P., Nartheh, L., Dogbe, W., and Wopereis, M. C. S. (2014). Sustainable rice production in African inland valleys: seizing regional potentials through local approaches. *Agricultural Systems* **123,** 1–11.

Roder, W., Phengchanh, S., Maniphone, S., Songnhikongsuathor, K., and Keoboulapha, B. (2001). Weed management strategies aimed at reducing labour for upland rice production. *In* "Slash-and-Burn Rice Systems in the Hills of Northern Laos PDR: Description, Challenges, and Opportunities" (W. Roder, ed.), pp. 93–102, International Rice Research Institute, Los Banos, Philippines.

Ruthenberg, H. (1980). "Farming systems in the tropics.," Third Edition/Ed. Clarendon Press, Oxford, UK.

Sahrawat, K. (2010). Reducing Fe toxicity in lowland rice with tolerant genotypes and plant nutrition. *Plant Stress* **4**, 70–75.

Sahrawat, K. L., Jones, M. P., Diatta, S., and Adam, A. (2001). Response of upland rice to fertilizer phosphorus and its residual value in an ultisol. *Communication Soil Science Plant Analysis* **32**, 2457–2468.

Saïdou, A., Tossou, R. C., Kossou, D., Sambieni, S., Richards, P., and Kuyper, T. W. (2007). Land tenure and sustainable soil fertility management in central Benin: towards the establishment of a cooperation space among stakeholders. *International Journal of Agricultural Sustainability* **5**, 195–212.

Sakurai, T. (2002). Land tenure systems and adoption of water control technologies in lowland rice production *In* "Economic analyses of agricultural technologies and rural institutions in West Africa – Achievements, challenges and application to rice farming research. Proceedings of JIRCAS international workshop" (T. Sakurai, J. Furuya and H. Tagaki, eds.), pp. 107-125. Japan International Research Center for Agricultural Sciences, Tsukuba, Japan.

Sakurai, T. (2006). Intensification of rainfed lowland rice production in west africa: present status and potential green revolution. *The Developing Economies* **44**, 232–251.

Sanchez, P. A. (1976). "Properties and management of soil in the tropics," John Wiley & Sons, New York, USA.

SAS Institute, I. (2004). SAS System Version 9.1. SAS Institute Inc., Cary, NC, USA.

Sebillotte, M. (1974). Agronomie et agriculture. Essai d'analyse des tâches de l'agronome. *Cahiers Orstom Série Biologie* **24**, 3–25.

Sebillotte, M. (1990). Some concepts for analyzing farming and cropping system systems and for understanding their different effects. *In* "Inaugural Congress, European Society of Agronomy", Paris.

Sebillotte, M., and Soler, L. G. (1990). Les processus de décision des agriculteurs - I. Acquis et questions vives. *In* " Modélisation systémique et systèmes agraires, décision et organisation" (B. e. al., ed.), pp. 93-117. INRA, Paris, France.

Seck, P. A., Diagne, A., Mohanty, S., and Wopereis, M. C. S. (2012). Crops that feed the world 7: Rice. *Food Security* **4**, 7–24.

Shibayama, H. (1992). Integrated management of paddy weeds in Japan: current status and prospects for improvement. *In* "International Symposium on Biological Control and Integrated Management of Paddy and Aquatic Weeds in Asia", pp. 161–177, Tsukuba, Japan.

Singbo, A., and Oude Lansink, A. (2010). Lowland farming system inefficiency in Benin (West Africa): directional distance function and truncated bootstrap approach. *Food Security* **2**, 367–382.

Stahr, K., Weller, U., Koch, W., and Igue, A. M. (1999). Land evaluation and land use planning in southern Benin (West Africa) – Suitability of the region for traditional and innovative production systems. *In* "Special Research Programme 308 “Adapted farming in West Africa”, Report of results 1997–1999" (U. o. Hohenheim, ed.), pp. 59-86, Hohenheim, Germany.

Stessens, J. (2002). "Analyse technique et économique des systèmes de production agricole au Nord de la Côte d’Ivoire." Katholieke Universiteit Leuven, Geel Huis, Kasteelpark Arenberg 11 bus 2100, B - 3001 Heverlee, Belgium.

Tamado, T., and Milberg, P. (2000). Weed flora in arable fields of eastern Ethiopia with emphasis on the occurrence of *Parthenium ysterophorus*. *Weed Research* **40**, 507–521.

Tenenhaus, M., and Young, F. (1985). An analysis and synthesis of multiple correspondence analysis, optimal scaling, dual scaling, homogeneity analysis and other methods for quantifying categorical multivariate data. *Psychometrika* **50**, 91–119.

Ter Braak, C. J. F., and Smilauer, P. (1998). CANOCO reference manual and users guide to Canoco for Windows: software for canonical community organization Microcomputer power, Ithaca, New York.

Thornton, P. K., Boone, R. B., Galvin, K. A., BurnSilver, S. B., Waithaka, M. M., Kuyiah, J., Karanja, S., González-Estrada, E., and Herrero, M. (2007). Coping strategies in livestock-dependent households in East and Southern Africa: a synthesis of four case studies. *Human Ecology Review* **35**, 461–476.

Tittonell, P., Muriuki, A., Shepherd, K. D., Mugendi, D., Kaizzi, K. C., Okeyo, J., Verchot, L., Coe, R., and Vanlauwe, B. (2010b). The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa – A typology of smallholder farms. *Agricultural Systems* **103**, 83–97.

Tittonell, P., Vanlauwe, B., Leffelaar, P. A., Rowe, E. C., and Giller, K. E. (2005a). Exploring diversity in soil fertility management of smallholder farms in western Kenya I. Heterogeneity at region and farm scale. *Agriculture, Ecosystems and Environment* **110**, 149–165.

Tittonell, P., Vanlauwe, B., Leffelaar, P. A., Shepherd, K. D., and Giller, K. E. (2005b). Exploring diversity in soil fertility management of smallholder farms in western Kenya II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. *Agriculture, Ecosystems and Environment* **110**, 166–184.

Tosh, G. C., Reddy, B. S., and Nanda, K. C. (1981). Integrated weed management in dryland rice. *International Rice Research Newsletter* **6**, 20–27.

Touré, A., Becker, M., Johnson, D. E., Koné, B., Kossou, D., and Kiepe, P. (2009). Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Cote d'Ivoire. *Field Crops Research* **114**, 304–310.

Touré, A., Mahamane, C. M., Becker, M., and Johnson, D. E. (2005). Approche diagnostique des interventions culturales dans les bas-fonds rizicoles de la Côte d'Ivoire. *Agronomie Africaine* **17**, 219-225.

Touré, A., Sogbedji, J. M., and Gumedzoé, Y. M. D. (2013). The critical period of weed interference in upland rice in northern Guinea savanna: Field measurement and model prediction. *African Journal of Agricultural Research* **8**, 1748–1759.

Tsubo, M., Basnayake, J., Fukai, S., Sihathep, V., Siyavong, P., Sipaseuth, and Chanphengsay, M. (2006). Toposequential effects on water balance and productivity in rainfed lowland rice ecosystem in Southern Laos. *Field Crops Research* **97**, 209–220.

Tuong, T. P., Castillo, E. G., Cabangon, R. C., Boling, A., and Singh, A. (2002). The drought response of lowland rice to crop establishment practices and N fertilizer Sources. **74**, 243–257.

Valbuena, D., Verburg, P. H., and Bregt, A. K. (2008b). A method to define a typology for agent-based analysis in regional land-use research *Agriculture, Ecosystems and Environment* **128**, 27–36.

van der Heyden, C. J., and New, M. G. (2003). The role of a dambo in the hydrology of a catchment and the river network downstream. *Hydrology and Earth Systems Science* **7**, 339–357.

Vanlauwe, B., Aihou, K., Houngnandan, P., Diels, J., Sanginga, N., Merckx, R., and (2001). Nitrogen management in adequate 'input' maize-based agriculture in the derived savanna benchmark zone of Benin Republic. *Plant Soil* **228**, 61–71.

Vissoh, P. V. (2006). Participatory development of weed management technologies in Benin, PhD thesis, Wageningen University, Wageningen, The Netherlands.

Vooren, A. P. (1985). "Patterns in tree and branch fall in a West African rain forest," Rep. No. Forest Report D 85–05. Wageningen Agricultural University, Wageningen, The Netherlands.

Weber, G., Elemo, K., and Lagoke, S. T. O. (1995). Weed in intensified cereal-based cropping systems of the Northern Guinea Savanna. *Weed Research* **35**, 167-178.

Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., and David, C. (2009). Agroecology as a science, a movement and a practice. A review. *Agronomy for Sustainable Development* **29**, 503–515.

Williams, J. F., Roberts, S. R., Hill, J. E., Scardaci, S. C., and Tibbitts, G. (1990). Managing water for weed control in rice. *California Agriculture* **44**, 7–10.

Windmeijer, P. N., and Andriesse, W. (1993). "Inland valleys in West Africa: An agro-ecological characterization of rice-growing environment," ILRI, Wageningen, the Netherlands.

Windmeijer, P. N., Dugué, M. J., Jamin, J. Y., and Van de Giesen, N. (2002). Describing hydrological characteristics for inland valley development. (P. N. Windmeijer, M. J. Dugué, J. Y. Jamin and N. Van de Giesen, eds.). WARDA/ADRAO, Bouaké, Cote d'Ivoire.

Wopereis, M. C. S., Kropff, M. J., Maligaya, A. R., and Tuong, T. P. (1996). Drought stress responses of two lowland rice cultivars to soil water status. *Field Crops Research* **46**, 21–39.

Wopereis, M. C. S., Johnson, D. E., Ahmadi, N., Tollens, E., and Jalloh, A. (2013). Realizing Africa's Rice Promise. CABI.

Workayehu, T., Mazengia, W., and Hidoto, L. (2011). Growth habit, plant density and weed control on weed and root yield of sweet potato (Ipomoea batatas L.) Areka, Southern Ethiopia. *Journal of Horticulture and Forestry* **3**, 251–258.

Yanggen, D., Kelly, V., T., R., and Naseem, A. (1998). "Incentives for fertilizer use in Sub-Saharan Africa: A review of empirical evidence on fertilizer response and profitability," East Lansing, Mich., U.S.A.

Zhang, X., Zang, R., and Li, C. (2004). Population differences in physiological and morphological adaptations of Populus davidiana seedlings in response to progressive drought stress. *Plant Science* **166**, 791–797.

Zhao, D. L., Atlin, G. N., Bastiaans, L., and Spiertz, J. H. J. (2006). Cultivar weeds competitiveness in aerobic rice; heritability, correlated traits, and the potential for indirect selection in weed-free environments. *Crop Science* **46**, 372–380.

Ziska, L. H. (2007). Climate change impacts on weeds. *In* "Climate Change and Northeast Agriculture: Promoting Practical and Profitable responses"